SOIL DRILLING BY VIBRATION

by

B. M. Gumenskii and N. S. Komarov

Authorized translation from the Russian

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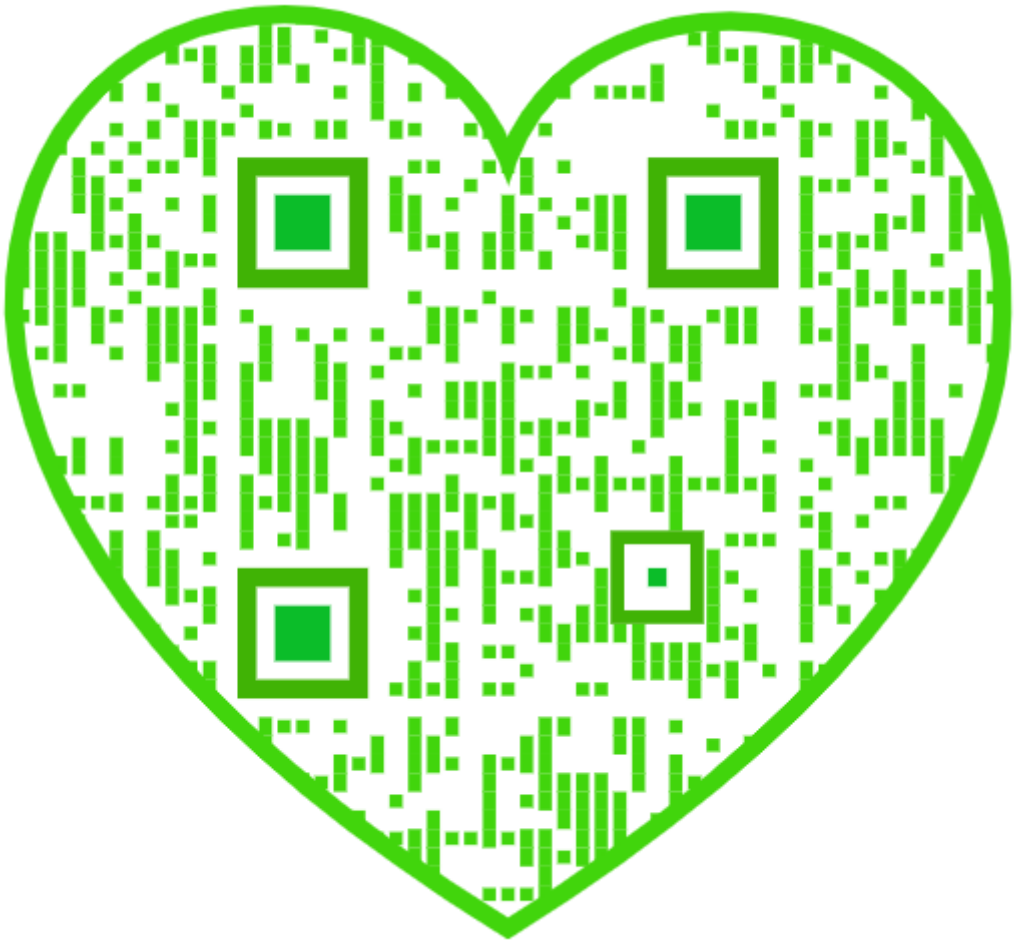

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VIBROBURENIE GRUNTOV

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PREFACE

A very promising new type of geological exploration tool, vibrodrilling in soils, has been introduced in recent years into the field of engineering-geological investigations. As tests on the use of vibrodrilling have shown, the technique is suitable for engineering-geological investigations on construction areas and on railroad and highway beds, and in prospecting and exploring for construction material and other mineral deposits. Vibrodrilling may be especially effective when drilling holes for roasting the soil, for the setting of sand piling, for horizontal and vertical drainage, and for treatment of ills in earthen railroad beds, i.e., for those circumstances when a precise geologic section is not required.

Even in the early stages of the use of vibrodrilling, when the existing equipment was imperfect, the penetration rate was 4-5 times that of manual percussion-rotary drilling, at the same time lessening the labor of the operators and furnishing more complete results.

However, the technique of vibrodrilling has been, until now, inadequately treated in the technical literature, and this fact has made it difficult to expand the use and development of the method.

This book is a generalization of experiments by various organizations and of special studies made by the authors at the Leningrad Institute of Railroad Transport Engineers, partly in cooperation with the Leningrad Institute for the Planning of Transportation of the Ministry of Transportation Construction.

Since one of the principal problems in vibrodrilling in clay soils is the behavior of the soils during vibration, this book devotes considerable attention to thixotropic alterations (liquefaction and subsequent solidification of soil) as the chief factor aiding the easy penetration of the drilling instrument (or other object) even in dense clay soils.

In analyzing the results of our investigations and tests on vibrodrilling, we kept in mind the following points as needing explanation:

1) the relationship between composition of colloidally dispersed minerals in the clay soils and their capacity to undergo thixotropic change;

2) the nature of the processes originating during vibrodrilling in clay soils, since there are no data at the present time on this problem;

3) the conditions under which the capacity to soften and liquefy appears during vibration in clay soils;

4) the relation of the capacity to soften and liquefy in clay soils to the effect of direct electrical current and ultrasonic waves;

5) the dimensions of the zone of softening or liquefaction in clay soils during vibrodrilling;

6) the degree of precision in describing and measuring geologic sections from vibrodrilling data;

7) the possibility of ascertaining hydrogeological conditions during vibrodrilling;

8) the degree of disturbance to a number of soil properties during vibrodrilling.

Other problems are also considered briefly in the book.

For some of these problems concrete solutions have been advanced, such as the instructions on methods of conducting vibrodrilling operations. In considering other problems, only the principal solution is discussed,

particularly in regard to the question of employment of electroosmosis during vibrodrilling, for which only the most feasible application is commented upon. For a number of other questions, the authors have confined themselves merely to scientific statements of the problems, very important preliminary steps, inasmuch as the problems are urgent but are as yet completely uninvestigated. This group of problems includes, in particular, imperative studies on the effect of ultrasonic waves and of active substances of various compositions for lowering and even completely removing the capacity of soils to undergo thixotropic alteration, on the one hand, and for increasing the process to a maximum, on the other.

It should be emphasized that, until recently, the process of liquefaction of soils by vibration has not received proper attention. Furthermore, thixotropic changes in soils have not even been mentioned in some courses on soil studies.

In order that the reader may become better acquainted with the thixotropy of dispersed systems in general and, in particular, with such systems as clay soils, the capacity of which to liquefy makes vibrodrilling and the vibratory sinking of piling or planking possible, basic information on thixotropy will first be discussed. At the same time several data on the effect of vibration on unconsolidated soils will also be alluded to. In addition, various existing designs of vibrodrilling equipment will be described, the degree of precision of geologic sections that are described from vibrodrilling data will be examined, and the principal methods of conducting vibrodrilling operations and of obtaining records from the holes produced will be pointed out.

The Introduction and Chapters I and II were written by Professor B. M. Gumenskii, Doctor of Geological-Mineralogical Sciences, and he was also responsible for the over-all editing of the book; Chapters III and IV were written by Docent N. S. Komarov, candidate in the geological-mineralogical sciences, from data obtained together with B. M. Gumenskii [25]*.

The authors deem it obligatory to express their gratitude to the Doctors of Geological-Mineralogical Sciences I. M. Gor'kova, for reading Chapters I and II in manuscript, and V. V. Popov, the editor of the book, for his notes on the manuscript, which have made it a better book.

Inasmuch as the present work touches on a number of completely new, partly controversial, questions, it is naturally not lacking in some defects. All notices of these and all friendly criticism the authors accept with gratitude.

The Authors

* The numbers in brackets here and in the rest of the volume designate references to the literature at the end of the book.

INTRODUCTION

It is well known that vibrators are widely used at the present time in the construction industry; these are special devices which, when turned on, produce high-frequency oscillations that are transmitted to the surrounding medium. Vibrators are used for various purposes: for compacting sandy soils and concrete, for sinking and extracting piling and planking, etc. In 1949, Professor D. D. Barkan (All-Union Scientific-Research Institute for Footings and Foundations) proposed the use of vibrations in sinking geological-exploratory drill holes. The successful testing of this technique led to the development of a new variety of geological-exploration operation—vibrodrilling, which quickly found wide application.

Several Leningrad organizations played important parts in the development and perfection of vibrodrilling techniques; these include the Leningrad Institute for the Planning of Transportation, the Leningrad Institute for River Transport Planning and Research, the Leningrad Railroad Engineers Institute, the Leningrad Design and Planning Institute for the Construction Industry, the Leningrad Trust for the Design and Planning of Hydroelectric Power Plants and Hydroelectric Developments, the All-Union Scientific Research Institute of Hydro- and Sanitary Engineering, the Leningrad Mining Institute, and the Leningrad Institute for the Design and Planning of Water Resources and Melioration Development.

Of Moscow organizations, in addition to the All-Union Scientific-Research Institute for Footings and Foundations, vibrodrilling has been applied by the Moscow Geological Trust, the Office for the Survey and Planning of Quarries for Transportation Requirements of the Ministry of Railroads of the USSR, and others.

The essence of vibrodrilling involves the fact that pulsations from a vibrator of some type (Fig. 1) are transmitted to the drill tip directly or through a drill rod, and these pulsations are then transmitted to the surrounding soil. As a result of high-frequency oscillations in the soil, there occurs a marked decrease in shear resistance, and because of this the drilling device, under its own weight and the weight of the vibrator, easily penetrates the soil. After the required depth is reached, the drilling device is raised by means of the vibrator, the drilled interval is logged and soil samples are taken. These indicated operations are repeated for penetrating successive intervals at greater depths until the requisite depth of examination is attained.

As with any new method, vibrodrilling needs further development and improvement, and also study of its application and a thorough evaluation of the results obtained. It should be noted, however, that, until recently, investigators turned their attention chiefly to developing the design of vibrators and to the compaction of sands [7-11, 21, 36, 67, 68, 75, 79]. The nature of the phenomena originating in soils during vibration have been but little studied. Even in relation to sands, the existing literature indicates no reference to the effect of mineral composition, grain size, grain shape, degree of rounding, or other such properties on the vibrations. Meanwhile, the investigations of V. V. Okhotin [50] and others showed that these indicated factors will determine the course of vibration. The inadequacy of studies on vibration processes in soils is also pointed out in a book of one of the leading specialists in this field, Professor D. D. Barkan [10]: "the physical processes that determine changes in soil properties during vibrodrilling and, in particular, the decrease of resistance to external loading *have not yet been clearly explained.*" (Italics ours.)

Whereas there has been but little study on the peculiarities of sand relative to its reaction to vibrators, the literature contains almost no discussions concerning such relations in regard to clay soils. However, it is precisely in clay soils that the effect of vibration will vary depending on the composition of the colloidally dispersed (clay) minerals and on the base exchange in such soils; i.e., physicochemical factors will play an important role, as was first pointed out in 1947 by Professor N. M. Gersevanov [21] and by B. M. Gumenskii, simultaneously but independently.* Both authors noted that thixotropy was observed in soils when piles were being driven and in the intervening intervals of quiet; i.e., the soils became soft and even liquefied, changing from gels† to sols under the

* See the report of the department of the Leningrad Railroad Engineers Institute, "Geology, Footings, and Foundations," for 1947 for the section of "Scientific-Research Papers."

† Dispersed systems, in which the particles of the disperse phase do not form continuous rigid structures and do not exhibit resistance to shear, are called sols or free dispersed systems. If the particles in the dispersed systems form spatial structures, networks or frameworks, such systems are called gels or coherent dispersed systems (Rebinder [38]).

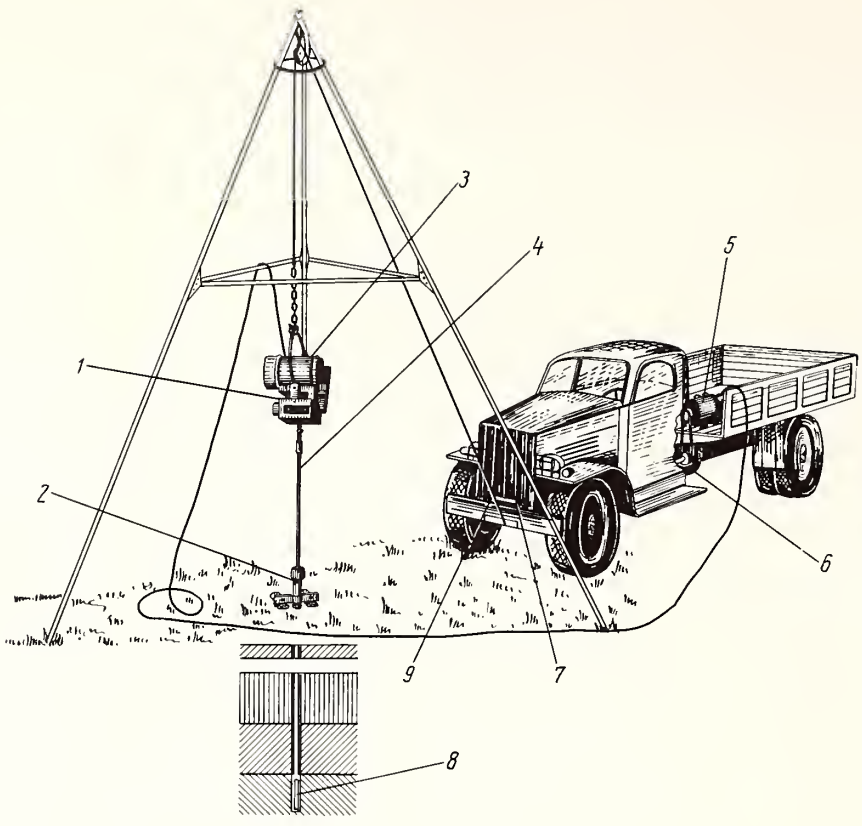


Fig. 1. General view of the vibrodrilling equipment designed by the Leningrad Institute for the Planning of Transportation. 1) Vibrator, 2) casing, 3) electrical vibrator, 4) drilling rod (d = 42 mm), 5) generator, 6) pulley, 7) hand brake, 8) drill bit (barrel), 9) drum hoist.

influence of vibration. In a certain zone about a sinking pile, thixotropy leads to destruction not only of the texture of the soil, but also of the structure; it determines the strength of the soil and produces along the end of the pile a transition from sol to gel and thus strengthens the ground.* The same situation arises during vibrodrilling.

From this it follows that the processes arising in clay soils during vibration should be thought of as physico-chemical.

In this regard, despite all its urgency in light of questions relative to the improvement of mechanization in the construction industry, brought before the engineers at the Twenty-First Congress of the Communist Party of the Soviet Union, the literature is still barren of any experimental data on the effect of vibration. The use of vibro-drilling permits us to make extensive studies in this matter with an economy of means.

A thorough study of thixotropic processes arising during vibrodrilling in clay soils, of the nature of thixotropic changes (liquefaction and solidification), and of the conditions favoring or hindering such phenomena permits one better to improve the design of vibrators and to establish proper technology in conducting vibrodrilling operations.

The meaning of thixotropy does not exhaust the problems associated with vibrodrilling and the sinking of piling and planking, but, as has been noted in the reports of the Third International Congress on Soil Mechanics and Foundation Problems (Switzerland, 1953), the phenomenon of thixotropy may be used to solve a number of other construction problems.

In the report of Professor Beder [91], a method is described for constructing an impermeable diaphragm at great depth by means of "thixotropic muds." This method involves the injection of bentonite suspension, which has well-defined thixotropic properties, into closely spaced drill holes. In drill holes with a radius of 30 cm, such suspensions will penetrate into the surrounding soil (sand) to a distance of 120-150 cm, and thus, by using a

* Under structure of dispersed systems (clay soils) we mean the structure of dispersed systems (soils) arising by mutual reactions between particles of the disperse phase and molecules of the disperse medium (water).

number of holes, one may create a screen impermeable to water. The cohesion of weakly bound soil is increased to 2-3 T/m^3 and more by the injection of such suspensions. The coefficient of permeability in gravel with fragments having a diameter of 10 cm is $1 \cdot 10^{-1}$ cm/sec for a particular sample; this value decreases to $3 \cdot 10^{-6}$ after injection, that is, the ground becomes practically impermeable to water. The concentration of such suspensions is 25 kg of dry bentonite for 100 kg of water. Suspensions in gravelly sands use 0.4 m^3 for each cubic meter of surrounding soil.

This same report makes note of the considerable predominance of this type of diaphragm for draining and isolating aquifers. It is shown that such a method of draining is reliable under the most complex geologic conditions, being usable in any soil at low cost. Diaphragms up to 30,000 m^2 in area have been produced at Volturno and at the dam across the Po River (Italy).

The value of thixotropy in clay soils for construction purposes also involves the fact that, depending on different conditions, the soils may act in the system of structures either as a "rigid" body or as a viscous liquid according to the pressures exerted on them. In proportion to the shear stress, a change occurs in the process at the point of transition from a "rigid" state to a viscous liquid. A certain interest in this relationship is manifested in the data of Chaplin and Newell [91]; according to these data, a plate sank under a pressure of 41 g/cm^2 in one of the muds having a disturbed structure. To cause this plate to sink in undisturbed mud, the mud being in a state of "calm," pressures ranging from 412 to 720 g/cm^2 were required.

The study of the capacity of clay soils to undergo thixotropic change under the influence of vibrations [30] has permitted a certain clarity to appear in the question of possible compaction of soils by vibrating devices [45, 79, 83].

The absence of sufficiently clear views concerning the processes arising in soils that have been subjected to vibration limits the use of vibrators for construction and other purposes. It is precisely the inadequate knowledge of these processes that has led to the cases of failure in using vibrators in the sinking of piling, the compaction of soils, and other tasks. There is special significance in the study of these processes when using vibrations for geological-exploratory purposes, inasmuch as by ignoring the processes we may derive an entirely erroneous concept of the nature of the soils investigated during a survey.

Chapter I

GENERAL INFORMATION ON THE THIXOTROPY OF VARIOUS DISPERSED SYSTEMS

§ 1. THIXOTROPY IN DISPERSED SYSTEMS AND THE PRINCIPAL ENVIRONMENT IN WHICH IT OCCURS

By thixotropy (from the Greek "thixis"—shaking—and "trope"—change) of dispersed systems in general, or of soils in particular, we mean their liquefaction during jarring by some mechanical action (shaking, stirring, etc.). Under such circumstances, at a constant temperature, there occurs a transition from gel to sol, which, after a certain time, is again converted to gel. Thixotropy should thus be considered to involve two aspects: liquefaction and solidification. These constitute a reversible process, since it may be repeated many times.

The possible occurrence of thixotropy in dispersed systems has been recognized for a rather long time. According to Professor H. Freundlich (G. Freindlikh) [82], who first began the study of thixotropy in various dispersed systems, the process may be outlined in the following manner. A concentrated gel of some substance containing hydrated particles linked to each other may, by some mechanical action, such as shaking, be reduced to such a disordered state that, when all the particles are in active Brownian movement, the gel becomes a sol. The quantity of liquid needed for this process should be sufficient to enable the particles to effect the Brownian movement.

Despite the fact that thixotropy has long been recognized as a process, scientists have not furnished a single opinion concerning its causes. In a survey of factual information on thixotropy, H. Freundlich has noted that the probable causes of thixotropy appear to be variable [82].* In his opinion thixotropy is "without doubt" due to forces of attraction and repulsion between particles in the sol or gel. He considered the proof of this view to lie in the clear relationship between thixotropy and coagulation, as confirmed by experiment. Moreover, several investigators consider the transition from sol to gel to be a coagulation process [82, 97, 98].

H. Freundlich associated the phenomenon of thixotropy "with the clear affinity between particles and liquid, leading to the formation of thick layers of liquid about the particles." In this process the particles swell and interlock under conditions such that the amount of liquid between pairs of particles is sufficient for thixotropy to occur on shaking.

In the thixotropy of gels an important role is played by the envelopes of hydrates,which surround the particles and impart a necessary incoherence to them under certain conditions. Thus, moistened quartz powder is not plastic and is not thixotropic. When montmorillonite is added, the mass becomes plastic and acquires the capacity of thixotropic conversion because of the development of envelopes of hydrates about the particles as a result of the added montmorillonite.

In his consideration of thixotropy H. Freundlich gave special attention to a factor of paramount importance, the form of the particles; he has noted that a nonspherical form is a "primary condition for the formation of thixotropic systems."

The next essential factor in the thixotropic process is the degree of dispersion of the particles. Experiments with Solnhofen limestones containing 1-2% clay (according to H. Freundlich) have shown that some of the particles should have a diameter of 1 μ or less; if almost the entire mass consists of particles with diameters of 10μ and greater, the system proves to be nonthixotropic. Similar data have been cited by Boswell, showing that the addition of 0.2% of Gault clays (by weight) makes the expansible (dilatant) nonthixotropic glauconitic Gault sand readily thixotropic.

It should be emphasized that, in considering questions of thixotropy, we must assign a definite significance to

* Among the materials investigated by H. Freundlich were many rock-forming minerals and many rocks. Despite the fact that all the materials were artificially crushed, many of the observed results of these studies are of definite interest for geologists and and construction engineers.

the size of the particles; an increase in size is detrimental to the thixotropic process. A particle dimension of 0.005 mm is taken as the limiting value. For particles of this size Brownian movements are easily observed.

In analyzing the relationship between thixotropy and the isothermal plasticity of dispersed systems, H. Freundlich has noted that "any system may be thixotropic if its particles are of colloidal dimensions and if they take part in the formation of sols and gels."

A similar view has been expressed by Winkler, according to which all substances, if they are sufficiently dispersed, may form thixotropic mixtures with an appropriate medium, such as water [99]. Suitable conditions for thixotropic processes may involve both crystalline and amorphous bodies. As will be shown below, the cited views have been completely justified in regard to clay soils.

It is thought that the time necessary for the change from sol to gel is a constant value for a given dispersed system under a given set of conditions. Different thixotropic systems solidify at different rates. According to H. Freundlich bentonite and ground Solnhofen limestone are converted to gel almost instantaneously, other systems after several minutes, and some mixtures after several hours and even days.

Interesting data have been supplied by Professor A. I. Avgustinik [1]; they have to do with the relative value of thixotropic solidification in clay masses as measured by definite increments in load (in grams) necessary for pressing a steel ball 5 mm in diameter into clay (covered with oil) to a depth equal to the distance the same ball (unweighted) sank into the clay immediately after the sample was prepared. Professor Avgustinik showed that thixotropic solidification continues in different clays for different lengths of time, in practice the minimum being 60 hr, the maximum 200 hr.

In analyzing the results of his experiments on clarifying the relationship between the value of thixotropic solidification and the moisture content of a porcelain-clay mass and bentonite, A. I. Avgustinik concluded that when the moisture content is small "the organization of thixotropic structure develops weakly. With increase in moisture content in the clay, the capacity for thixotropic transformation increases and reaches a maximum at some optimum value, specific for each type of clay. With greater moisture content in the clays, the distance between clay particles increases, and the effect of these forces thus diminishes. When the moisture content is very high, when the particles are actually in suspension, the value of these forces falls practically to zero." The development of "thixostructure," as A. I. Avgustinik calls it, and the thixotropic solidification of clay masses at constant moisture content are associated by this investigator with a type of base exchange of the clay particles.

That thixotropic systems do not immediately regain the structure and value of limiting shear stress after they are disturbed, but only after some time of thixotropic "congelation," has also been reported by N. V. Tyabin [78].

We have obtained different data in experiments on the vibrodrilling of partly indurated Lower Cambrian clays: the time necessary for changing the clay from a state of viscous liquid to a plastic or partly semisolid state, depending on the total moisture content, is measured in minutes. These experiments have shown that the less the natural moisture in the soil the quicker the soil is restored to its initial physical state. We have noticed also that semisolid clay, after the samples were taken from a hole made by vibrodrilling, changed from the state of viscous liquid again to a semisolid, but not to a plastic, state.

Thus, the time of gelatinization will be different for different dispersed systems. For soils, this time is apparently determined primarily by the concentration of particles during the transition into a state of liquefaction. The greater the concentration, the shorter the time will be for gelatinization. The composition of the colloidally dispersed minerals is also a definite factor, since minerals have different affinities for water. In soils containing montmorillonite, the time of gelatinization will be greater than in soils containing kaolinitic and hydromicaceous particles.

At the end of his survey, H. Freundlich has noted that "despite significant analogies in the behavior of various thixotropic systems, there are great differences between such systems. . . loose packing and the development of structure due to equilibrium between the forces of attraction and repulsion are their general features. But the nature of these forces (whether they are due to reactions between particles or molecules or whether they are simply electrostatic) may be very different in different actual systems."

From all these data it may be seen that the phonomenon of thixotropy may be manifested only in soils containing clay particles and a certain quantity of water. Thixotropy is not seen in soils containing no clay particles (sands, gravels, etc.). If, when drilling such soils (sands), the drilling apparatus is observed to sink a hole rather easily, the explanation may be found in entirely different causes. In this case there is produced merely a jarring of the bond between particles, which move relatively to each other, and this leads to a sharp decrease in friction of the drilling apparatus in the sand. When using vibration under the influence of gravity and external loading, if this technique is used, the particles tend to occupy new, more stable positions, and, as a result, the sand is compacted by the vibration.

§ 2. THE STRUCTURE OF GELS IN CLAY SOILS

The capacity of clay soils for thixotropic transformations is directly related to the structure of their gels. It would apparently be more nearly correct to consider that the particles in the gels form a framework, such as that illustrated in Fig. 2a, b, and c [17]. Water is found in the cells (pores—p) of this framework. However, until recently such an opinion has been based most commonly on purely theoretical considerations rather than on direct observations or on other actual data. There is therefore considerable interest in the data of A. Weis, R. Fan, and U. Gofman [92], by which the presence of such a framework is demonstrated by driving off the liquid from a thixotropically solidified gel congealed in a strong vacuum. It was shown that, after elimination of the liquid, the *volume of the desiccated sample* (Fig. 3b), in most cases, even at room temperature, *was almost as great as the volume of the moist gel* (Fig. 3a). The authors believe that such a phenomenon is possible only when the particles in the thixotropically solidified gel are in direct contact.

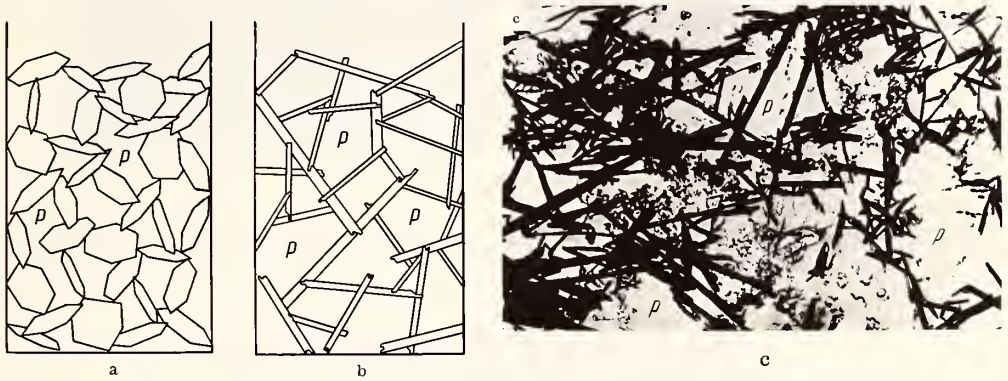


Fig. 2. Schematic diagram of the framework in thixotropically solidified gel: a) "house of cards" of platelets (kaolin), b) framework of needles (halloysite), c) halloysite (electron-microscope photograph).

In connection with this, the data in Table 1 deserve our attention; here are listed changes in some of the properties of thixotropic gels of clay, depending on the kind of colloidally dispersed minerals composing them.

From Table 1 it may be seen that, despite the complete elimination of water, the volume of almost all the clay samples was practically the same, and, at the same time, these samples were able to withstand rather heavy loads.

In describing their experiments and, in particular, in noting the low mechanical strength of the frameworks for halloysite gel (see last line in Table 1), the authors explain that this framework consists of needles and tubes (Fig. 2c), whereas the framework for kaolinite and bentonite consists of platelets (Fig. 2a). Desiccated samples of Na-bentonitic gels exhibit striking elasticity, as seen from the following data. One such sample was compressed to three-quarters its length and, after removal of the load, it returned to its original volume, like a sponge. The authors of the experiments explain this phenomenon by saying that "the solid particles are held together at points of contact by rather strong forces, while the particles themselves are elastic, flexible platelets." This elasticity, in their opinion, is in agreement with electron-microscope data, by which it may be observed that particles of montmorillonite are very thin.

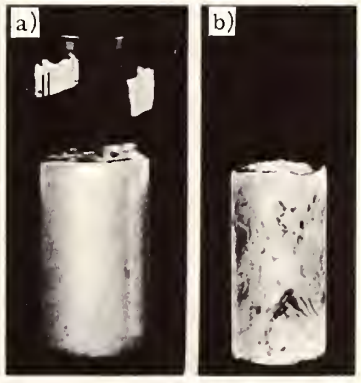


Fig. 3. Thixotropically solidified gel: a) gel of 0.138 g of Na-bentonite and 2.475 g of distilled water; b) freely standing bentonitic sample (0.141 g) after desiccation through glass tubing (diameter of bentonite particles less than 5μ). Magnification, ×1.3.

The views expressed above concerning the framework structure of clay-soil gels, advanced also by Byuchli, are supported by the data of Academician P. A. Rebinder [62] and of N. N. Serb-Serbina and N. A. Nikitina [73]. In considering the problem of the nature of gelatinization of clay suspensions, these workers have noted that a "reticulated" structure forms in this process (Fig. 4). In regard to this N. N. Serb-Serbina has written: "Elongated scales of clay are joined by their ends (edges) through highly thinned hydrate envelopes in these 'active centers of coagulation.' In this process the dispersing medium is captured in cells formed by the reticulated structure."

Investigations with the electron microscope have shown that the particles of clay differ markedly in form. If they are montmorillonite (Fig. 5), the outlines are indistinct, suggesting clouds, with some grains or accumulations of grains ranging up to 1μ and more in long dimension; if the particles are kaolinite, they have the form of hexagonal platelets (Fig. 6), which can hardly be called "elongated scales," as the flakes of hydromica may, for instance (Fig. 7).

Table 1

Relationship between Bearing Value of Different Clays and Their Mineral Composition

Clay	Liquid content in thixotropic gel per g of clay	Time of solidification, in sec, in tubes 1.8 cm in diam.	Vol., in cm^3, of thixotropic gel per g of clay	Vol., in cm^3, of desiccated sample per g of clay	Wt. of expelled liquid, in g, per g of clay	Load on desiccated sample, g/cm^2
Na-bentonite	13.60 g dist. H_2O	4—5	14.0	~14.0	13.58	~25.00
Na-bentonite	18.00 g "	150	18.4	~18.4	17.94	~24.00
Na-bentonite	18.00 g "	150	18.4	~18.4	17.93	~21.00
K-kaolin	1.60 g "	4—5	2.0	~2.0	1.51	~160.00
K-kaolin	1.60 g "	4—5	2.0	~2.0	1.58	~160.00
K-kaolin	5.28 g benzene	6—10	6.4	~5.4	4.97	~1.58
K-kaolin	5.10 g "	6—10	6.2	~4.9	4.80	~1.35
Ca-kaolin	2.40 g dist. H_2O	4—5	2.8	~2.3	2.38	~50.00
Halloysite from Dzhebel-Debar	3.47 g "	4—5	3.9	Fissured with large cavities	3.39	Crumbles even on slight shaking

Explanation: 1) The content of liquid in the thixotropic gel (column 2) was determined by the decrease in liquid on weighing the clay and the liquid.

2) The time of gelatinization was the time of rest (column 3) necessary for the gel, after shaking, to become sufficiently solid not to flow out when the tube was inverted.

3) The quantity of expelled moisture (column 6) was determined by weighing before and after the moisture was driven off.

4) The volumes of gel before moisture elimination (column 4) and after elimination (column 5) were determined by successive measurements of water.

5) The load (column 7) was determined by application to a free-standing desiccated sample consisting of a column with a cross-sectional area of 2.2 cm^2 or to a cube the edge of which was 1 cm long.

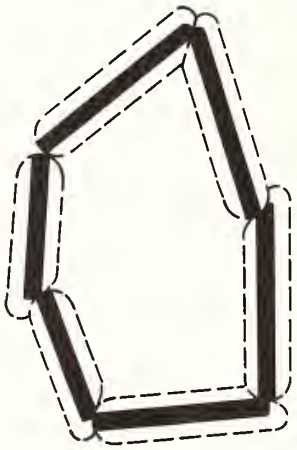


Fig. 4. Diagram showing orientation of clay particles, according to P. A. Rebinder and N. N. Serb-Serbina (reticulated structure).

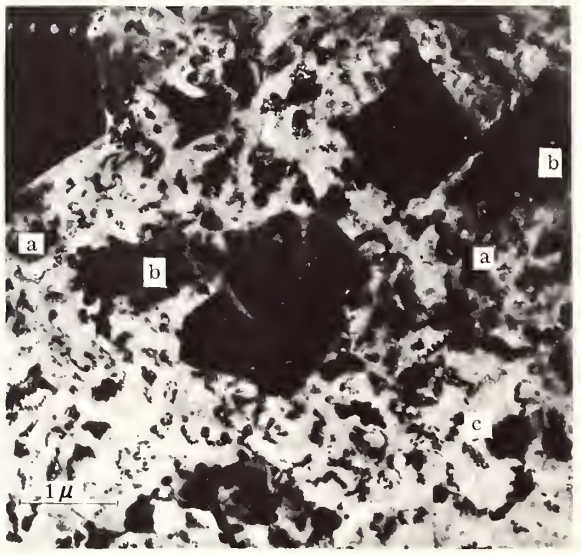
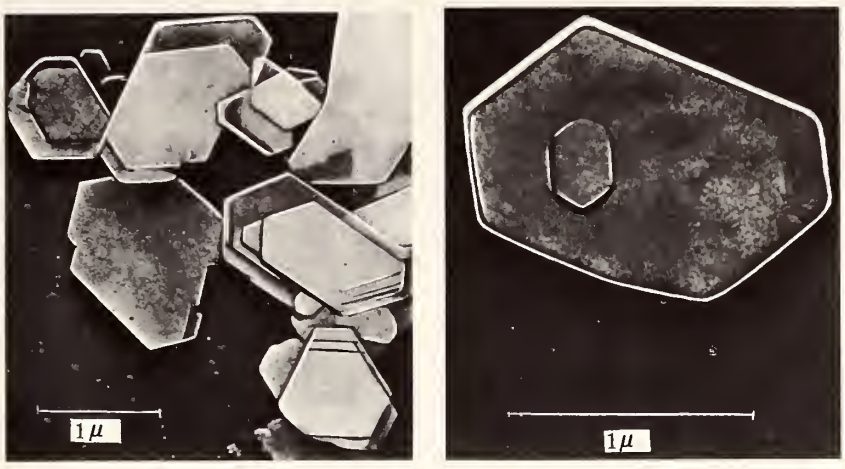


Fig. 5. The form of particles smaller than 0.001 mm in the Turkmen bontonite: a) a mass of fine scales of montmorillonite, b) disseminated large crystals of montmorillonite, c) slightly swollen montmorillonite or gel-like nontronite. Magnification, ×20,000.



a b

Fig. 6. Crystals of kaolinite, with dimensions of 0.4-0.8μ: a) a group of crystals, b) an individual crystal. The reflection (shadow) is three times the actual thickness of the particle.

Fig. 7. The form of particles smaller than 0.001 mm in Lower Cambrian clays consisting of hydromica (a) and sericite (b) with admixtures of kaolinite (c).

It was noted above that the development of a structure of some degree of mechanical strength in a clay suspension and the mechanical properties of this structure are determined by the coagulation of the solid particles. Different types of reticulated structures (coagulation structures) arise, depending on the intensity of coagulation in the suspension: from loosely reticulated structure, uniformly filling the entire volume of the suspension, to individual compact aggregates [73]. The intensity of coagulation also depends to a certain degree on the nature of the surfaces of the clay particles; this determines the relation of the particles to the water, the degree of dispersion, and the relative proportion of solid phase to the medium, i.e., the number of particles per unit volume.

The electrolytes, (which control the coagulation of the solid particles) that are present in the clays are divided by several investigators into two groups [72]. The first group includes soda, lithium carbonate [72], and other alkaline electrolytes, which, after exchange adsorption, generate hydrophilic properties on the internal and external surfaces of the clay particles and thus facilitate dispersion. At some optimum content of such electrolytes in the clay solutions, hydrophilic coagulation is produced. The second group includes electrolytes with multivalent

cations; they produce hydrophobic properties (dehydration) on the surface of a particle. It is thought that such changes on the surfaces of particles enable the particles to be linked over the entire surface, thus forming compact aggregates and leading to hydrophobic coagulation, in contrast to hydrophilic coagulation, during which the contacts between particles are made at small pointed areas at active sites on the surfaces, where the layer of hydrates becomes extremely thin.

§ 3. METHODS OF DETERMINING THE CAPACITY OF CLAY SOILS TO UNDERGO THIXOTROPIC ALTERATION

The simplest method of determining the capacity of clay soils to undergo thixotropic alteration, i.e., the time of gelatinization (solidification), is the method of the "inverted test tube." This procedure involves placing the prepared suspension in the tube and shaking it. It is then possible to set the tube in a stand. The time is measured from the moment of shaking the suspension to the instant when the contents of the tube are no longer able to flow out.

As Winkler has noted [94], when the "inverted tube" method is employed, it is necessary to keep in mind that the phenomenon of thixotropy becomes less noticeable the larger the diameter of the tube. The height of the column of suspension in the tube also affects the results of the experiments. Therefore, in order to obtain comparable data, it is necessary to conduct all experiments under identical conditions. There are several modifications of the described method.

Observations have shown that the time of gelatinization of clay soils depends markedly on the concentration of the electrolytes in them. Their gelatinization is entirely analogous to the phenomenon of solidification and time of coagulation of hydrophobic sols. The time of solidification decreases with an increase in the concentration of electrolytes. In this process the effect of valence of oppositely charged ions obeys the same laws that hold for the coagulation of more diluted sols. This analogy has been traced also to the relationship of temperature on the time of solidification. In both cases the time of gelatinization decreases with increase in temperature (see below, § 10).

The time of gelatinization, apart from the effect of temperature, "is especially sensitive to the presence of various admixtures in the gel" [82], a fact that may be confirmed by the change in pH in the solution. The time of gelatinization decreases with an increase in pH (Table 2). In this process some substances (metals) accelerate the gelatinization, others (amino acids, such as glycerin) cause liquefaction; this is considered a confirmation of the view that thixotropy and coagulation are similar.

Table 2

Effect of pH on the Thixotropy of Iron-Oxide Sols (after H. Freundlich)

Quantity of NaOH and HCl (in millimoles per liter)		pH	Time, sec
NaOH	6.30	3.86	82
NaOH	5.40	3.78	140
NaOH	4.50	3.73	200
NaOH	3.60	3.65	300
NaOH	2.70	3.56	440
NaOH	1.80	3.50	750
NaOH	0.90	3.43	1300
NaOH	0.45	3.39	About 1600
NaOH	0.00	3.37	" 2000
HCl	0.45	3.32	" 3300
HCl	0.90	3.26	" 4800
HCl	1.80	3.18	" 6600
HCl	2.70	3.11	" 9000

Thus, at first glance, a crude method ("inverted test tube") of describing the thixotropic behavior of gels and of determining the times of gelatinization gives rather closely reproducible results, in the opinion of Professor I. I. Zhukov [35a]. This is clearly the reason that the method is widely used, especially in foreign countries [94].

However, in using this method it is necessary to remember the warning of Yu. S. Zuev [35a] that the instant of visible transition from sol to gel ("time of gelatinization") is but one point on the gelatinization curve, after which the strength of the gel continues to increase. It is clear that the "time of gelatinization" of a system, the determination of which, until recently, has been the extent of our studies of thixotropy, is purely a qualitative characteristic of thixotropic transformation after the mechanical destruction of the structure.

In considering the primitive character of the "inverted test tube" method for determining the capacity of soils for thixotropic transformation, Professor A. I. Avgustinik proposed a different method in 1939 [2]. The basis of this method lies in the increase in shear resistance of the solidified system, and "requires that this property be measured at various points in the investigated system, the points being at least 15 mm apart [B. M. Gumenskii] because, if the thixotropy of the system is to be studied throughout the entire solidified mass by, for example, inverting a test tube, the process of testing destroys the initial structure, and subsequent inversions of the tube may not give comparable figures." The deviation in moisture content for the different test points has been taken as 0.5%. A special device has been designed for these tests (Fig. 8).

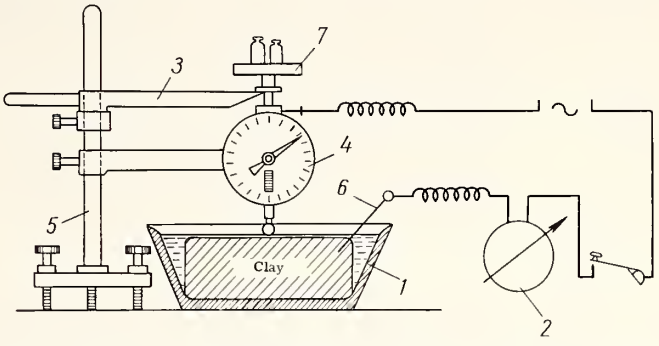


Fig. 8. Sketch of A. I. Avgustinik's apparatus: 1) pan, 2) voltmeter, 3) lever, 4) gauge, 5) stand, 6) electrical conductor, 7) platform for load.

In this apparatus a layer of plastic clay 15 mm thick is placed in a pan (1); the surface of the clay is covered with a thin layer of oil, and a pin with a sphere 5 mm in diameter at the end is lowered to the surface of the clay. The instant of contact between sphere and clay is indicated on a voltmeter (2) because the contact closes the electrical circuit. A lever (3) is removed at the side, and the sphere, acted on by the weight of the load, is pressed into the soil. The pressing action is allowed to continue for one minute. It is then possible to measure the depth of the impression with a gauge (4).

The increase in mechanical strength, as measured by such impressions in thixotropically solidified material, is determined by repeating the experiment some hours later. In order to determine the magnitude of the depression an auxiliary weight is placed on the platform (7).

The results of investigations using the described apparatus are shown in a diagram (Fig. 9), on which the ordinate axis indicates values of thixotropic gelatinization τ and the abscissa represents time in hours. The value of τ is determined from the relationship

$$\tau = \frac{P_1 - P_0}{P_0} 100, \qquad (1)$$

where P_0 is the initial load, equal to 75 g, and P_1 is the final load necessary to bury the sphere to some standard depth.

In order to compare the values of thixotropic induration of various clays, measurements were made at intervals of 20 hours after the beginning of each experiment.

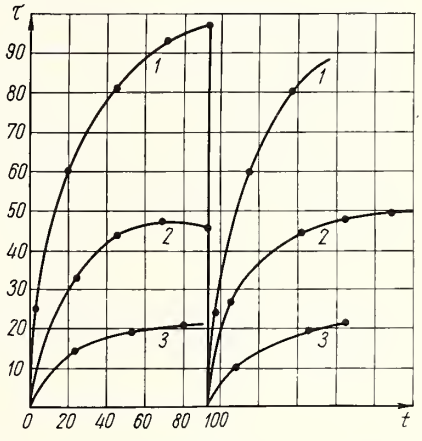


Fig. 9. Curves for thixotropic induration of various clay soils: 1) porcelain-clay mass, 2) Ryazhsk clay "Zh," 3) kaolin elutriated in air.

Other investigators believe that, in studying thixotropy, it is necessary to determine the characteristics of the structure, since the transition from sol to gel is a structure-forming process.

Academician P. A. Rebinder and his students have shown that the basic characteristics of structural development in clay soils and of the associated phenomena of thixotropy are indicated by the structural-mechanical properties—coefficient of rigidity*—and the elasto-plastic (relaxational)* and elasto-kinetic properties [18, 72, 73], the initial studies of which were made as early as 1899 by the Russian scientist

* As is well known, a normal liquid begins to flow at the slightest tipping of a vessel. In order for a liquid having structure to flow, the liquid being a clay colloidal system, it is necessary to impose a certain force to destroy the structure. Only when a certain value of stress is attained, exceeding the shear resistance of the liquid, does the liquid begin to flow. The static or initial shearing stress is similar to the value for critical (yield point) shearing resistance in solid bodies.

* By relaxation we mean the process of decrease in stress with time.

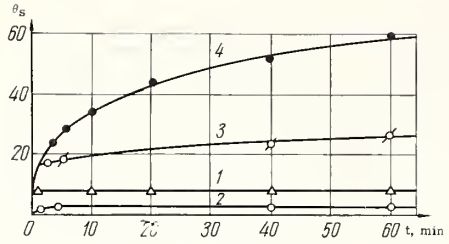


Fig. 10. Kinetics of structural development according to measurements of the static limit of shear in a 20% suspension of Krasnokamsk clay in the presence of Na_2CO_3 (after N. N. Serb-Serbina): 1) suspension in water, 2) in 0.1% solution of Na_2CO_3, 3) in 0.25% solution of Na_2CO_3, 4) in 0.5% solution of Na_2CO_3.

F. N. Shvedov. Rebinder and his students believe that the capacity for clay soils to undergo thixotropic transformation is rather well defined by the gradual increase of each of the indicated properties with time as the soil remains at rest. Kinetic curves of this type (Fig. 10) graphically illustrate the development of a structural network, since, as seen from Fig. 10, they make it possible to determine when the limit, characterizing the greatest strength, has been reached.

It is precisely the above-indicated properties of clay soils that represent the cause of anomalous values of viscosity that have been observed; this fact points up the great desirability of investigating the elastoplastic characteristics, as being more expedient than taking readings on a viscosimeter. However, in speaking of the coefficient of rigidity in clays, i.e., the property inherent in solid bodies, it should be emphasized that this coefficient, in contrast to actual solid bodies, is extremely variable and subject to the effects of relaxation. Because of this, clay soils behave like distinctly flowing material under certain circumstances, failing to preserve their form when acted on by gravity.

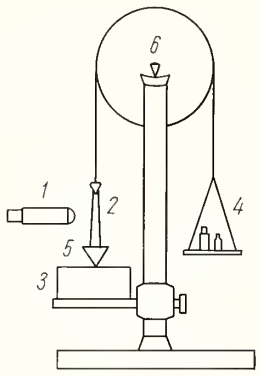


Fig. 11. Diagram of a cone plastometer: 1) microscope viewer, 2) microscale, 3) the system being investigated, 4) counterbalance, 5) cone, 6) pulley.

The grounds for determining the direct mechanical characteristics of the structure are found in the fact that thixotropic processes are characterized by the "spontaneous development of structure with an increase in mechanical strength during the structural growth" [71]. P. A. Rebinder and his coworkers have proposed a number of techniques for measuring the shearing limit P_m [18, 38]; one of these methods involves use of a cone plastometer by which the kinetics of penetration, $h = f(\tau)$, is measured in the investigated system by means of a cone acted on by a constant weight F [38, 71]. However, it should be pointed out that this method has all the disadvantages characteristic of nonstationary methods.

The cone plastometer (Fig. 11) consists of a steel cone with a sharp circular cut on the lateral surface to prevent slipping. The cone is suspended from a thread, which passes over a special pulley and has a counterweight at the other end. To eliminate corrections for friction an aluminum disc, with a steel prism placed at the center of mass to serve as a bearing, is used instead of an ordinary pulley. After the cone is placed in contact with the surface of the investigated sample, one of the weights constituting the counterweight is removed and the penetration is measured by means of a horizontal microscope viewer and a microscale fastened to the shaft of the cone. The average value of P_m is computed by the maximum penetration of the cone for different loads.

The vessels in which the experiments are conducted are about 5 cm deep and 4 cm across, and the effect of the bottom and walls on the measurements is thus eliminated.

The acting shearing stress is determined by the following formula:

$$P = \frac{F \cdot \cos(\alpha/2)}{S} = k_\alpha \frac{F}{h^2}, \qquad (2)$$

where the coefficient, depending on the angle of the cone, is

$$k_\alpha = \frac{1}{\pi} \cos^2(\alpha/2) \cot(\alpha/2);$$

where α is the angle of an axial section of the cone and F is the constant load, related to unit area.

The value of P decreases in direct proportion to the penetration, because of the increased area of displacement, the area of contact S between the cone and the system. Correspondingly, the rate of penetration of the cone also decreases, $V = dh/d\tau$, until it becomes practically zero for large penetrations, $h = h_m$.

The critical shearing stress P_m, i.e., the maximum static stress possible in a given soil, is also equal to the smallest value of the actual stress:

$$P_1 = P_m = \lim P \text{ when } V \to 0 \text{ and } h \to h_m,$$

which corresponds to equilibrium of the external forces F of plastic strength of the structure. From this it may be

seen that the described method permits us to obtain rather simply and reliably the rheological characteristics—the flow curve, which shows the relationship between rate of penetration, $dh/d\tau$, and the shear stress, P.

Academician P. A. Rebinder and E. E. Segalova [71] have shown that the value

$$P_m = k_\alpha \cdot \frac{F}{h_m^2} \text{ g/cm}^2 \qquad (3)$$

should be near the limiting static shear stress, i.e., the greatest static stress possible in the given system. The value of P_m, defining the plastic strength of the system, may be computed by formula (3) (which contains no empirical constants) by the maximum penetration of the cone, h_m, produced by a given load, assuming that flow occurs along the lateral surface during penetration of the cone into the system.

This condition is realized in rather plastic systems, a fact, according to P. A. Rebinder and E. E. Segalova, demonstrated in these circumstances by the practically invariant value of P_m, i.e., by the independence of P_m of the size of the device (cone) and of the form of the vessel and also of the load F and the cone angle α.

In systems that have greater strength and are brittle, flow is replaced by impression during penetration of the cone. In this process the independence of the load, i.e., of the maximum depth of penetration (h_m), is preserved, but the results of the testing begin to depend on the apex angle of the cone α (P_m increases with increase in α). Under these circumstances the coefficient k_α in equation (3), which expresses the effect of the cone angle, loses its meaning.

We should note in conclusion that some authors, in evaluating the capacity of soils to undergo thixotropic transformation, investigate indirect data, striving to discover some particular, pertinent relationships. This is very important since in this direction one may obtain the greatest results with the least expenditure of research effort. Thus, data show that the coefficient of porosity ϵ of clays having different colloidally dispersed minerals (Fig. 12) is greater for montmorillonitic clays than for hydromicaceous and kaolinitic clays (it may be the same for the latter two). From this it may be concluded that the higher the coefficient of porosity in soils the greater the capacity for thixotropic transformation will be manifested.

This view is also indicated by data on the strength of soils, shown below in Table 12 (column 9). These data direct one's thoughts to the fact that the stronger the capacity of clay soils for thixotropic transformation the lower their relative strength in a plastic state. However, because of the paucity of facts, this view cannot be conclusively confirmed, especially in view of the fact that graphic representations of the results show a great scattering of points.

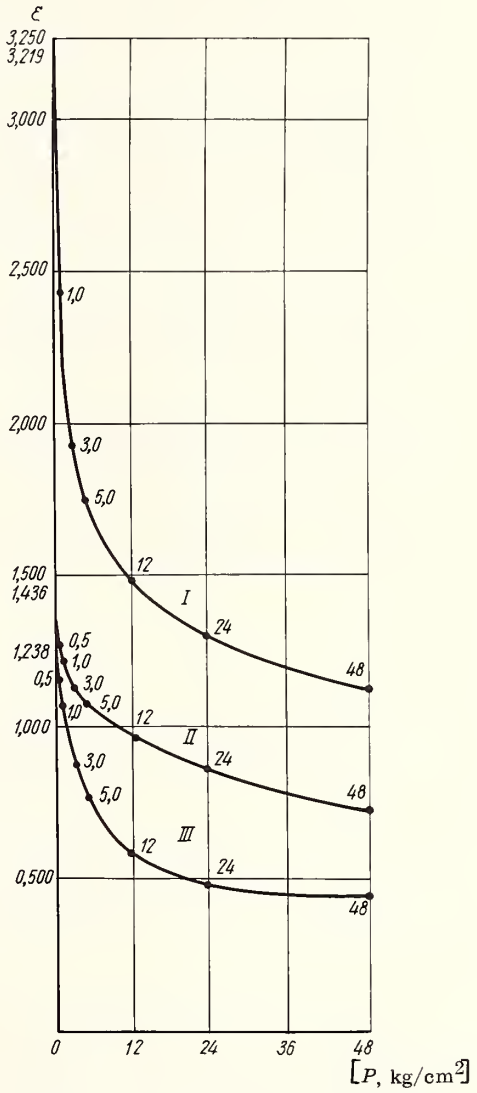


Fig. 12. Compression curves for some clays: I) Turkmen bentonite, II) Glukhovetskii kaolin, III) Lower Cambrian clay.

§ 4. VIEWS CONCERNING THE EFFECT OF VIBRATION ON INCOHERENT SOILS

Professor G. I. Pokrovskii, D. D. Barkan, and other investigators have conducted numerous experiments to study the effect of vibration on incoherent soils [10]. These experiments have established the following conclusions:

1. The coefficient of internal friction for dry sand (freshly piled) increases sharply after vibration.

2. The moistening of sand generally decreases the effect of vibration on changes in the physicomechanical properties.

3. The change in coefficient of internal friction in sand during vibration depends on the acceleration (rate) of vibration; the greater the frequency, the lower the coefficient of internal friction becomes.

4. The characteristic of the mechanical properties of soil may possibly be expressed by means of the coefficient of "viboviscosity," since soil, when shaken, acquires the properties of a viscous liquid. This coefficient is meant to represent the proportionality factor between the load acting on the vibrating body and the established rate of penetration, which depends essentially on the vibration rate. The coefficient of vibroviscosity depends also on the moisture content of the sand, since the cohesive force in soils depends on the moisture content in the ground.

Experiments have shown that the coefficient of vibroviscosity, equal to 63.6 poises for dry sand, increases to 13,800 poises for sand with a moisture content of 13.6%; i.e., it increases approximately 220 times. However, on further increase of moisture in the sand, the coefficient of vibroviscosity decreases sharply, and at a moisture content of about 20% it reaches a value the same as for dry sand. From this D. D. Barkan has assumed that, other things being equal, "vibrating devices will penetrate soils at the slowest rate when the sand is dry or contains moisture approaching the total possible for that sand."

5. When some other material, such as metal or wood, is used against soil, the internal friction of the soil is reduced by vibration. This fact is illustrated in the following data from D. D. Barkan. In order to extract a No. 55 I-beam, which had been driven 17 m into the ground, a force on the order of 80 tons was required. By using vertical vibration with an amplitude of 4 mm and an angular frequency of 70 sec, a force of only three tons was required. Thus, when the beam was vibrating, the frictional forces acting on it decreased to almost one-thirtieth the value of the frictional forces acting when the beam was extracted under static conditions.

6. The compaction of the sand depends on the character of the vibration—on the amplitude and the frequency. Porosity decreases with increase in amplitude and frequency. A characteristic that has been found to define the relationship between change of porosity in the sand and the vibration constants is the increase in frequency or, more precisely, the inertial force acting on the particles during vibration. Since the latter is proportional to the specific gravity of the particles, other things being equal, sands with greater specific gravity will compact more strongly than sands with particles of lesser specific gravity.

7. The directive factor of vibration does not affect the compaction of the sand. Regardless of whether the vibration is in the vertical or horizontal plane the sand is compacted in a similar manner, and, when the frequency is constant, the compaction is determined by the amplitude of the vibration.

8. The behavior of sand during vibration may be shown on a vibration-compression curve, on which the abscissa shows the ratio of vibratory acceleration to acceleration of gravity, η, and the ordinate indicates the coefficient of porosity, ϵ, (Fig. 13).* From the figure it may be seen that the curve is similar to the ordinary compression curve and may be expressed analytically.

9. The size of particles affects the length of time required to compact the sand. With an increase in size the time required for compaction corresponding to a given frequency decreases.

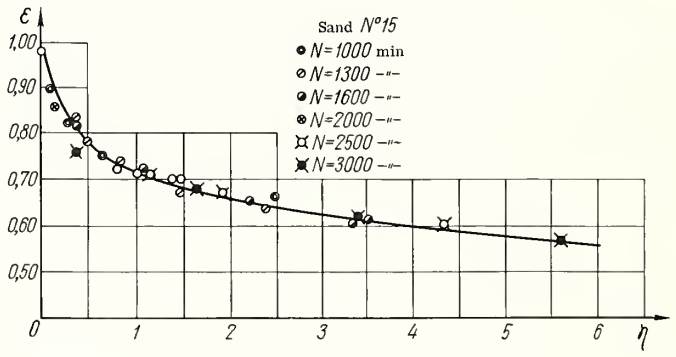


Fig. 13. Vibration-compression curve.

10. In order to define more precisely the effect of vibration on sand it is necessary to introduce the concepts of "threshold of vibratory compaction" and "zone of vibratory compaction." As is well known, static stresses produce residual deformation if they exceed the elastic limit. In exactly the same way vibration produces compaction if the vibration frequency exceeds a certain value, which D. D. Barkan has called the threshold of vibratory compaction (threshold of vibrocompaction). Thus, if the sand has a coefficient of porosity ϵ, which corresponds to vibration frequency η_0 on the vibration-compression curve, vibrations with a frequency less than η_0 produce no change in ϵ. Consequently, sand may be compacted by vibration only when

* The various symbols on the curve designate number of vibrations per minute.

$$\eta > \eta_0, \tag{4}$$

where η_0 is the threshold of vibratory compaction, i.e., the vibration frequency corresponding on the vibration-compression curve to the coefficient of porosity of the soil before vibration, and η is the ratio of vibration frequency to gravitational acceleration.

The concept of "threshold of vibratory compaction" permits us to determine the dimensions of the zone of compaction in sand produced by a given process of vibration. It is clear that, during local excitation of elastic waves in sand, the acceleration of the oscillations will be determined by the distance from the source of excitation. Near the source the amplitude of the waves will be greater than farther away; i.e., the value of ϵ, as affected by vibrations from a local source, is a variable quantity, depending on changes in acceleration in the particular segment of ground. In this regard D. D. Barkan believes that the "boundary of the zone of vibratory compaction in the soil is a surface equal in value to the acceleration of the oscillations; consequently, the determination of the dimensions of the zone of compaction reduces to a computation of the *field of acceleration of the oscillations* in the ground produced by a given vibrator, particularly by the basement or substratum" (italics by D. D. Barkan).

Further, on the basis of experimental investigations on the vibration-compression properties of sands, O. Ya. Shekhter has also brought to light the following relationships [88]:

1. A factor affecting the compaction of sand by vibration is normal pressure. The greater this pressure the less sand is compacted by vibration. The compaction, in such circumstances, generally begins with some frequency at a higher threshold of vibratory compaction.

2. If the coefficient of porosity of a given sand is less than the coefficient of porosity of a sand corresponding to a definite frequency on the vibration-compression curve, it may be expected that there will be no compactions at frequencies less than or equal to that value.

3. The effect of initial porosity for dry and water-saturated sands is shown only in the value of the threshold of compaction. At frequencies greater than the compaction threshold, the vibration-compression curve does not depend on initial porosity.

4. The compaction of water-saturated sands differs little from that of dry sands, especially at high frequencies. When normal pressure is absent, water-saturated and dry sands are better compacted than sands with other moisture contents. The least compaction of sand is obtained when the moisture content is 6-8%.

5. The more heterogeneous sands are in coarseness, the better they are compacted by vibration.

6. The lower the coefficient of porosity, the greater the degree of compaction the sands obtain by vibration.

§ 5. SUMMARY

On the basis of the material discussed above, the following conclusions may be made:

1. Clay soils, being dispersed structural systems, occupy an intermediate position, in their physical properties, between liquids and solids, approaching the first or the second depending on the degree of development and strength of the structural network (framework). The presence of such structure lends clay soils plasticity and other such properties.

2. The phenomenon of thixotropy is defined as the capacity for isothermal reversible change from a sol to a gel during mechanical disturbance to the bonds in the framework of the soil. These bonds, determining the development of structure, are restored in time, and this tends to change the mass into a gel. In other words, it is necessary to consider the conversion from sol to gel as an oriented process, occurring at different times of coagulation and being accompanied by immobilization of the entire liquid phase.

3. The intensity of coagulation depends on the nature of the surfaces of the clay particles relative to water, and it depends on the number of particles per unit volume. The nature of the particle surfaces may be changed by the introduction of various materials into the water to change the conditions of hydration on the surfaces and, consequently, the character of the aggregate state.

4. Of the methods to determine the thixotropic properties of soils, and by which these properties may be studied, the following should be mentioned: a) the "inverted test tube" method, b) the method of Professor A. I. Avgustinik, and c) the method of determining the characteristics of structural development (the school of Academician P. A. Rebinder). Of these, the first method permits us to obtain purely a quantitative characteristic of thixotropic transformation in soils, and it may therefore be used only for the roughest approximate determinations.

The method of A. I. Avgustinik and the determination of structural-development characteristics make it possible to evaluate quantitatively the capacity of soils to undergo thixotropic transformations.

5. It is most proper to maintain that the particles in clay soils form a framework, the interstices of which contain water; the framework may be preserved even on removal of the water.

6. The discovery of several relationships has permitted us to make quantitative evaluations of a number of phenomena originating in sands during vibration.

7. Despite all that has been discussed, it should be emphasized that the thixotropy of soils has been studied but very little, and it is therefore obvious that we must explain in this way the absence of views by scientists on a whole series of matters relative to this problem.

Chapter II

THIXOTROPY IN SOILS AND THE EFFECTS OF VARIOUS FACTORS ON IT

§ 6. THE RELATIONSHIP BETWEEN THIXOTROPY AND THE DEGREE OF DISPERSION IN SOILS

In § 1 we noted in the most general way that one of the factors determining the capacity of soils to undergo thixotropic transformation is the degree of dispersion, since on this property depends the total and specific surface area of soils; it determines the degree of activity in the reaction of the particles with each other and with the enviroining water. There is therefore interest in the data of H. Freundlich [82] that "quicksand" containing about 2% fine plastic clay lost its thixotropic properties when the clay was flushed out; i.e., it is sufficient for soil to contain altogether but 2% clay to become thixotropic.

The data in Table 3, which show the grain-size distribution in soils subjected to vibration during drilling, fully support the above-cited view concerning the effect of the clay fraction on the capacity of soils to undergo thixotropic transformations.

In this connection interesting data have been obtained from an experiment on studying clay solutions with markedly colloidal bentonitic clay—askangel (a colloidal bleaching clay from Askana in the Georgian SSR [13]); the experiments were conducted by A. I. Tsurinov, who was assisted by V. L. Kvirikashvili [86]. Two and a half grams of this clay was passed through a screen with 10,000 openings per cm^2 and then mixed immediately with 10 cm^3 of water to give a solution having 20% residue after two days. A gel was obtained only by doubling the amount of soil (5 g). If the sample of 2.5 g of askangel was first moistened with 0.5-1 cm^3 of water and the thick paste thus obtained was then ground in a mortar for 5-10 min, after which the remaining water was added (to make 100 cm^3), the solution was immediately converted to a gel. In this procedure the capacity for thixotropic conversion of the 5% and 2.5% solutions proved to differ. In the 2.5% solution, prepared by grinding the paste, thickening occured rather quickly after shaking and conversion to a fluidal state. The 5% solution of askangel thickened after a much longer interval of time. The thixotropic properties of the 2.5% solution resulted from increased dispersion, of the 5% solution from greater concentration of the solid phase. Consequently, thixotropic properties are due chiefly to the degree of dispersion of the solid phase in a solution.

From these data A. I. Tsurinov has written that it is clear that "at lower concentrations but with a greater degree of dispersion of the solid phase, thixotropic properties are manifested in greater measure than in solutions with high concentrations but with a low degree of dispersion of the solid phase. Solutions in which the solid phase is incompletely dispersed have thixotropic properties [capacity for thixotropic transformation—B. M. Gumenskii] that are manifested in greater degree the higher the concentration, i.e., at a greater specific gravity (of colloidal clays); when the concentration is insufficient, i.e., at lower specific gravity, thixotropic properties do not appear at all, and such solutions even yield daily residues."

In other words, in different solutions prepared from precisely the same clay the capacity for thixotropic transformation may appear only where there is a certain degree of dispersion of the solid phase, since even the highly colloidal askangel not only fails to thicken but even forms a residue when the solid phase is insufficiently dispersed in the solution.

The data of H. Freundlich cited above, confirming our own investigations, is of considerable interest, since it not only points out the importance of the degree of dispersion but also stresses the significance of the quantity of clay particles necessary to impart the capacity of thixotropic transformation to the soil. At the same time, these data do not throw light on the problem as a whole, since other fractions may also play a certain part. From this point of view it is significant to note the statement of Professor Boswell [94] that soils containing many particles of silt (0.05-0.005 mm) and sand are "less thixotropic" than soils in which these fractions are less abundant.

A very crucial factor in this matter has been discussed by N. M. Gersevanov [21]: in considering the "necessary conditions for thixotropy in soil," he has pointed out that "the soil must contain colloidal material no larger

Table

Some Data on the Characteristics of a Number

Specimen No.	Origin of the soil	Source	Sample depth, m	Grain-size distribution (%), particle size in mm								
				>2	2-1	1-0.5	0.5-0.25	0.25-0.05	0.05-0.01	0.01-0.002	0.002-0.001	<0.001
1	Fill	Sh-1	1.20-1.25	1.0	1.4	2.5	4.8	48.8	15.00	13.0	8.1	5.4
2	"	Sh-1	2.55-2.60	1.3	2.3	3.4	5.0	46.9	21.3	13.4	3.4	3.0
3	Moraine	Sh-1	3.75-3.85	4.5	1.7	0.5	5.3	30.6	23.2	18.4	6.0	9.8
4	Fill	Vs-1	1.10-1.20	0.5	1.0	3.0	3.7	44.6	20.9	16.1	3.4	6.8
5	"	Vs-1	2.55-2.60	1.1	1.6	0.5	6.4	47.0	19.8	14.2	3.3	6.1
6	Glacial (moraine)	Vs-1	3.15-3-20	1.0	1.6	3.8	5.5	42.5	21.9	15.0	4.5	4.2
7	"	Vs-1	3.75-3.85	1.7	1.5	2.2	2.2	41.0	22.0	16.5	3.8	9.1
8	"	Vs-1	5.00-5.10	1.0	1.0	3.2	4.1	34.6	23.7	18.9	4.3	9.2
9	"	Vs-1	4.05-4.10	2.4	1.8	2.4	4.3	33.5	23.2	18.2	4.9	9.3
10	"	S-1	3.15-3.20	1.1	1.8	0.3	5.2	44.6	21.9	14.0	5.0	7.1
11	"	S-1	6.50-6.60	0.1	0.5	0.2	3.0	43.2	25.1	15.1	4.1	7.7
12	"	S-2	3.15-3.20	1.3	2.0	0.2	5.6	45.4	22.0	14.6	3.6	5.3
13	"	S-2	4.05-4.10	0.3	1.3	0.3	5.5	46.9	17.4	16.8	3.6	7.9
14	Light loam	Vs-2	1.85-1.95	—	—	0.9	1.2	37.9	21.8	14.7	5.5	18.0
15	"	Vs-3	0.85-0.90	—	0.3	0.2	0.9	49.3	18.5	8.7	4.7	17.4
16	"	Vs-4	0.95 1.00	1.5	1.5	3.7	3.9	51.2	11.8	6.3	3.1	17.0
17	Glacial (moraine)	—	11.05-11.5	Not determined								
18	Marine		15.5-15.7	Not determined								
19	Fill	Vs-1	1.85-1.95	1.0	2.1	3.1	7.0	46.8	19.8	13.0	3.1	4.1
20	"	Sh-1	4.05-4.15	0.3	1.5	2.8	5.0	37.2	23.5	18.1	3.4	8.2
21	"	Sh-1	4.60-4.70	3.1	1.9	2.8	5.4	22.2	26.8	25.4	5.1	7.3
22	"	Sh-1	5.00-5.10	2.2	2.0	3.2	5.0	27.0	25.8	23.9	2.0	8.9
23	"	Sh-1	5.50-5.55	2.2	1.9	3.2	5.2	27.5	25.6	21.5	4.5	8.4
24	Alluvial	Sh-2	0.90-0.95	—	0.2	0.1	2.9	43.2	16.9	12.5	2.6	21.6
25	Alluvial	Sh-2	1.35-1.40	—	—	0.1	0.3	47.5	24.4	4.9	3.5	19.3
26	"	Sh-2	1.70-1.75	—	—	0.1	3.7	78.3	10.6	3.8	0.3	3.2
27	"	Sh-2	2.00-2.05	—	—	0.5	204	62.6	10.1	3.4	0.5	2.5
28	"	Sh-2	2.20-2.25	—	0.2	0.9	159	58.9	12.0	5.7	0.9	5.5
29		Sh-2	2.50-2.55	—	0.9	0.9	150	73.1	5.9	1.7	0.7	1.8
30	"	Sh-2	3.00-3.05	—	—	0.1	3.2	88.6	6.7	0.7	0.7	—
31	"	Sh-2	3.80-3.85	0.2	0.9	0.2	1.0	58.5	21.7	2.4	0.2	0.9
32	"	Sh-2	4.05-4.10	—	—	0.1	5.0	79.2	11.1	2.1	2.5	—
33	"	Sh-2	1.40-1.45	3.6	2.5	5.7	8.6	47.2	12.7	5.2	2.8	11.7
34	"	Sh-3	1.65-1.70	—	—	3.4	107	71.0	6.1	3.1	1.2	4.5
35	"	Sh-3	1.45-1.47	—	—	0.7	0.8	54.2	16.9	8.5	3.6	15.3
36	"	Sh-3	1.55-1.65	—	—	0.9	1.4	38.4	16.4	12.9	5.2	24.8
37	"	Sh-3	1.65-1.69	1.0	1.1	3.5	118	67.8	5.3	2.9	1.0	5.6

Explanation: Symbols in column 3 signify test pit (Sh), vibrodrilled hole (Vs), and hand-drilled hole (S).

of Investigated Soils from Various Sources

Soil type	Physical state (as observed in field)	Natural moisture content (w)	Sp gr of soil, g/cm³ (γ)	Sp gr of mineral constituents, g/cm³ (δ)	Porosity (p), %	Degree of water saturation (g)	Plasticity			Liquid index (W_l)	Maximum molecular moisture (W_{mmm}), %
							upper limit (W_m), %	lower limit (W_p), %	plasticity index (W_m-p), %		
Light loam	Plastic	14.10	1.92	1.68	36.00	0.554	23.50	14.10	9.40	0	10.32
Heavy sandy loam	Dense	21.73	1.74	1.43	46.70	0.656	—	19.17	—	—	—
Moraine	Plastic	16.02	2.07	1.73	34.45	0.828	25.00	16.3	8.70	0.03	—
Light loam	Slightly plastic	12.01	2.16	1.92	28.90	0.797	22.10	13.55	8.55	0.18	10.09
Heavy, silty, sandy loam	Slightly plastic	19.75	2.04	1.70	36.00	0.924	23.90	14.90	9.00	0.54	10.29
Heavy, silty, sandy loam	Plastic	19.30	2.13	1.79	33.00	0.100	20.30	13.10	7.20	0.86	10.30
Light loam	Slightly plastic	13.69	2.13	1.87	31.10	0.822	23.70	15.80	7.90	0.27	10.79
"	"	14.21	2.12	1.85	31.80	0.862	24.60	13.20	11.40	0.09	10.46
"	"	15.30	2.20	1.90	30.25	0.968	28.20	16.30	11.90	0.08	11.59
"	"	23.03	1.82	1.48	44.60	0.764	—	11.40	—	—	—
"	Plastic	20.27	2.08	1.75	35.60	0.985	22.17	12.32	9.85	0.81	9.96
Heavy sandy loam	"	21.44	1.77	1.45	46.50	0.668	26.10	17.20	8.90	0.48	11.21
Light loam	"	17.53	1.92	1.63	40.10	0.712	23.90	15.40	8.50	0.25	10.48
Heavy loam	"	21.35	—	—	—	—	35.33	20.15	15.18	0.08	—
"	"	20.00	—	—	—	—	34.39	21.39	13.00	9.17	—
"	"	22.30	—	—	—	—	34.88	17.89	16.99	0.26	—
Loam	Slightly plastic	21.70	2.07	1.70	37.50	98.3	26.00	18.00	8.00	0.46	—
Clay	Semisolid	22.75	2.05	1.67	38.60	98.4	41.00	20.00	21.00	0.13	—
Heavy sandy loam	Dense	23.52	1.67	1.35	49.10	0.538	—	—	—	—	—
Light sandy loam	"	13.57	2.07	1.82	32.90	0.750	—	—	—	—	—
"	"	15.98	2.10	1.81	33.20	0.867	—	—	—	—	—
"	"	14.91	2.18	1.89	30.55	0.916	—	—	—	—	—
"	"	13.80	2.15	1.89	30.60	0.858	—	—	—	—	—
Heavy loam	Nearly semisolid	18.49	2.05	1.73	32.60	0.882	—	—	—	—	—
Heavy loam	Dense, dry	19.98	2.03	1.69	36.30	0.927	—	—	—	—	—
Light sandy loam	Dry, medium dense	12.74	1.75	1.55	42.40	0.465	—	—	—	—	—
Fine sand	"	12.78	1.96	1.73	35.20	0.627	—	—	—	—	—
Heavy sandy loam	"	12.55	1.84	1.64	38.60	0.516	—	—	—	—	—
Sand	Dry, medium dense	6.46	1.66	1.55	41.80	0.243	—	—	—	—	—
Fine sand	"	9.78	1.61	1.46	44.90	0.318	—	—	—	—	—
"	"	8.04	1.81	1.69	37.18	0.322	—	—	—	—	—
"	"	21.4	1.88	1.54	42.60	0.776	—	—	—	—	—
Light loam	Plastic	19.32	1.93	1.62	40.80	0.768	—	—	—	—	—
Heavy sandy loam	Medium dense	13.47	2.02	1.78	32.60	0.738	—	—	—	—	—
Medium loam	Slightly plastic	20.30	—	—	—	—	—	—	—	—	—
Heavy loam	"	21.30	—	—	—	—	—	—	—	—	—
Heavy sandy loam	Medium dense	17.40	—	—	—	—	—	—	—	—	—

than 0.001 mm and must not have any notable quantity of material larger than 0.01 mm, since the large particles settle too quickly." The first point of N. M. Gersevanov substantiates the above-cited data of H. Freundlich; the second point is not explained. Moreover this second condition is inappropriate, since sand is always present in considerable quantities in the fraction larger than 0.01 mm, as seen in Table 3; from this table it may be seen that the quantity of particles greater than 0.01 mm in soils is commonly greater than 60-70%.

It is impossible to agree with N. M. Gersevanov in his explanation of a cause, which, in his opinion, excludes the possible presence of a "marked quantity" of particles of this size (0.01 mm) in the soil if thixotropy is to appear. N. M. Gersevanov has not considered the data on the strength of structures in clay sediments that develop when the clays pass from a sol to a gel. This high structural strength is confirmed by the universally known fact concerning the role of clay muds during drilling. As is well known, the structure in the clays prevents the settling of mud to the bottom of the hole when the drilling fluid is not circulating, since the settling particles must overcome the structural bonds between clay particles. Our investigations on the structural strength of monomineralic clays (Turkmen bentonite, Glukhovetskii kaolin, and Lower Cambrian hydromicaceous clays) have also shown that, under certain circumstances, the strength may be so high that sand (Fig. 14) poured on the gel in a graduated beaker is unable to penetrate the gel. This phenomenon is due to the existence of a structural network or framework in the gel, not destroyed by the pressure of the sand. In such examples it is impossible to ignore the process of structural development, a process that is determined, to a considerable degree, by the mineral composition of the colloidal fraction of the sediments.*

The data of H. Freundlich and other authors, including the data of Table 3, permit us to discard the second point of N. M. Gersevanov; it should not be considered necessary for changing soil into a state of liquefaction or into a soft mass during vibration.

In this case, as shown in Table 3, it is important merely that a certain quantity of material smaller than 0.002 mm be present in the soil, material capable in some measure and under certain circumstances of participating in Brownian movement, which determines the development of structure in soil, i.e., the transition from sol to gel.

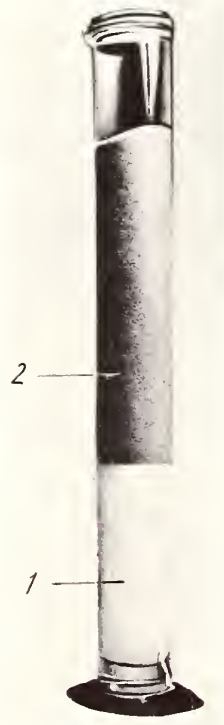


Fig. 14. Photograph illustrating the strength of bentonitic clay (Turkmen bentonite): 1) bentonite, 2) sand.

This conclusion is also forced upon us by the data of Academician P. A. Rebinder [63], which, in defining the conditions of thixotropy, indicate, as one of the requirements of this property, ". . . the presence of colloidally dispersed phase, i.e., the presence of particles actively participating in Brownian (thermal) movements"; the author clarifies this idea with the following words: "Actually, only thermal movements determine the statistics of impact-encounter of particles, a process that forms, under favorable conditions, cohesive linkage, the number of links increasing uninterruptedly with time (the kinetics of thixotropic growth of structural strength)." "Thus," P. A. Rebinder concludes, "a colloidal fraction is a necessary condition for thixotropy. . . The colloidal fraction, the number of particles of which dominates even in a comparatively small mass, plays the role, so to speak, of a coagulant mucilage, binding the spatial structural network of coarsely dispersed particles, forming, as it were, knots in the network, and becoming a distinctive, active filler."

§ 7. THIXOTROPY IN SOILS AND ITS RELATIONSHIP TO THE COMPOSITION OF THE COLLOIDALLY DISPERSED MINERALS

In considering the question of the effect of degree of dispersion in soils on the manifestation of thixotropy in such soils, it would be improper to ignore the composition of the associated colloidally dispersed minerals, since the total and specific surface area in the soils depends to a great extent on these minute particles with dimensions less than 0.002 mm. In addition, it is well known that the properties of soils containing clay particles depend, to a considerable degree, on which group makes up the colloidal part: montmorillonite, kaolinite, or hydromica. It is therefore important to consider the relationships between composition of the colloidally dispersed minerals in soils and the thixotropy of the soils.

Above all it should be emphasized that this question has almost never been discussed in the literature. There is definite interest in the data of Professor

* Professor B. V. Deryagin [31] believes that structurless clayey soils may exist. In his opinion, "it is improper to maintain without direct and reliable experimental proof for each individual case that a structural network is present in soils." We cannot agree with this statement, since it contradicts the well-known position of soil scientists on the structural makeup of soils and, in particular, of clays [26, 58, 63].

Boswell [94], who conducted his experiments with the "inverted test tube" method. He established the following thixotropic limits, expressing the content of water (in grams) per 100 g of solids*: kaolinite, 70-95%; halloysite, 80-100%; minerals intermediate between kaolinite and halloysite, 110-120%; hydromicaceous (illitic) clays, 110-170%; beidellitic clays, 170-250%; attapulgitic (palygorskitic) clays, about 530%; and montmorillonitic clays, 700-1350%.†

Deserving of attention are the remarks of Professor Boswell concerning the increase in capacity for thixotropic transformation in those clays (as has been observed in the London clays) that are "prepared" before the experiment by being left in contact with a small quantity of water. Boswell found the explanation of this phenomenon in the content of illite or of a related mineral in the London clay; these minerals, according to Grimm, have properties similar to bentonite, "by which illite takes up water within as well as around the lattice structure."

The data of Boswell cited above fail completely to disclose the relationship between the composition of the colloidally dispersed minerals in the soils and their liquefaction when the liquefaction is produced by vibration. Such data, generally speaking, are not to be found in the literature. Therefore, in order to explain the role of the colloidally dispersed minerals, we shall take advantage of the data we have obtained in studying the effect of vertical vibration on altering a number of properties of the Turkmen bentonite (montmorillonitic clay), Lower Cambrian hydromicaceous clays, and Glukhovetskii kaolinite [30].

As a criterion for determining the role of any particular colloidally dispersed mineral, the increase with time in structural strength of the clay was chosen for this investigation. The increase in structural strength was determined by the penetration into the soil of a brass cone having an angle of 30° and a weight of 116 g, and having a sharp spiral groove to prevent slipping. The cone was pressed into the clay by means of a special "consistometer," which permitted the depth of penetration to be measured with an accuracy up to 0.01 mm. The clay was set in vibration by means of a special device, a vibrator with a frequency of 4000 oscillations per minute and an amplitude of 1 mm [14, 15].

In one set of experiments the moisture content corresponded to the lower limit of flow, W_m; in another set the moisture corresponded to the plastic limit in the tube, W_p; and in the third the value adopted was the average of W_m and W_p. These moisture contents were chosen because they are associated with a definite physical state of the clay, what has been referred to in samples as disturbed structure.

In all, three series of experiments were run. In the first the clay was not subjected to vibration; in the second a particular mass of clay in a jar was subjected to vibration three times, for 5, 10, and 15 min, after which, in each case, depth of penetration of the cone was carefully measured successively after lapses of 1/2, 1, 2, 3, 5, 8, 10, 12, 15, and 20 min. To complete this latter experiment, i.e., to test for a vibration of 20 min and to make the subsequent measurements of penetration of the cone, the soil in the jar, in some runs, was "rested" for a day. After this interval the depth of penetration of the cone was measured.

This kind of experiment ("rest" of the sample) was carried out to test the effect of "rest" of the clay on the structural strength. In the third series of experiments a new mass of clay was used for vibrating for 10 min and for 15 min (in contrast to using the same clay as was done in the second series); the same initial moisture content was employed as in the second series and the same conditions of vibration were imposed. Further, the clay samples in the jars were also "rested" for a day, after which the depth of penetration of the cone was measured. The arrangement of this series of experiments should make apparent the effect of repeated vibration on the degree of structural strength with time; i.e., there were pauses after each vibration during which the samples "rested." The results of the experiments were worked up by constructing graphs showing the relationship between time and depth of penetration of the cone.

Omitting all the details relevant to the indicated experiments, which are described in the literature [30], let us note only the principal conclusions based upon them.

1. The most prolonged vibration (within 15 min) produced compaction of the clays, the compaction being greater the longer the vibration lasted, without regard to the initial physical state; i.e., the structural strength was determined by the duration of vibration alone. This phenomenon is explained by the fact that the vibration apparently produced a redistribution of particles in the clays, leading to a greater density of packing in association with the appearance of free water through transformation of some part of the physically bound water during the vibration [25, 28]. This water formed something of a lubricant and made possible easier movement of the particles relative

* By thixotropic limit we mean the ratio of volume of liquid to volume of solids in the soil mixture at a definite moment, when, after a minute's pause, the mixture will not flow when the test tube is inverted, but will flow freely if shaken or agitated.

† On the basis of these data Boswell, among others, concluded that the determination of thixotropy by the "inverted test tube" method may apparently be a simple, rapid field method for determining the principal group of colloidally dispersed minerals in soils.

to each other. In this process a definite role was played by the immobilized water in the cells of the framework, water that had been freed during the disturbance of that framework.

This conclusion gained confirmation in the paper of P. A. Rebinder [64], in which is written: ". . . vibratory action, shattering the structure and breaking the bonds, effects a decrease in strength, as is well known, and this facilitates the penetration of a post into the soil. In addition, such vibratory action may produce. . . extensive compaction and, because of this, a contrary effect [termed by him a paradox of practical significance—B. M. Gumenskii]—high strength" in the soil, as we have stated.

2. The effect of vibration on the structural strength of clays of different mineral compositions has been shown in the following way. When clays with an initial moisture content of W_m were subjected to vibration for 15 min, the greatest strength was found in hydromicaceous (Lower Cambrian) clays, since they were compacted only 12.5%; a lower structural strength was observed in kaolinitic clays (Glukhovetskii kaolinite), which were compacted 14.6%, and the least strength was measured in montmorillonitic clays (Turkmen bentonite), which were compacted 35.4%. A similar relationship has been demonstrated by other experiments we have performed, the composition of the colloidally dispersed clay minerals having been shown to affect in a similar way the structural strength [26].

An explanation for the greater compaction of the Turkmen bentonite must apparently be sought in the content of diffused water in these clays greater than in the Lower Cambrian clays or the Glukhovetskii kaolin. Diffused water was found to represent 37% of the Turkmen bentonite, 18.5% of the Blukhovetskii kaolin, and 16% of the Lower Cambrian clays. These determinations were made by continuous desiccation [29] at a temperature of 102°C; the initial moisture of the samples was approximately the same as in the samples tested for penetration of the cone.

3. The degree of compaction in the clays increased with time in proportion to the length of time the vibration was continued (within 15 min). This relationship is emphasized by the data of all the experiments regardless of the mineral composition of the clays and regardless of the physical state of the clays.

4. A somewhat different relationship, as compared with point 2, was observed between the structural strength of clays of the various compositions and the other initial moisture. Experiments have shown that with a moisture content of $\frac{W_m + W_p}{2}$ and W_p kaolinitic clays (Glukhovetskii kaolin) have the greatest structural strength, montmorillonitic clays (Turkmen bentonite) less, and hydromicaceous clays (Lower Cambrian) least. The cited data make it possible to state that a change in the physical state of the clays during vibration involves also a change in the effect of the composition of the colloidally dispersed minerals on the structural strength of the clays.

5. A comparison of the depths of penetration of the cone into clays of various mineral compositions for corresponding intervals of time of vibration (10 and 15 min) show that the penetration was greater when the same mass of clay was subjected to vibration than when a new mass of clay was used for the longer periods of vibration. This relationship was found to be systematic in all the experiments for all the clays, regardless of the mineral content and of the moisture content $\left(W_m, \frac{W_m + W_p}{2}, W_p\right)$. The cause of this phenomenon is to be found in the fact that the first series of vibration intervals in the experiments were not for 10 min but for 15, since the samples were subjected to vibration for 5 min before experiments testing the effects of 10 min of vibration. And samples vibrated for 15 min were really vibrated for 30 min (5 + 10 + 15), since they had already been vibrated for 15 min (5 min in the first phase and 10 min in the second phase). The longer period of vibration, despite a pause of 20-25 min for measuring the depth of penetration of the cone, led to a greater penetration, and this fact must apparently be explained by loosening of the compaction in the clays during repeated vibration.

6. After a "rest" (when the same mass of clay was subjected to vibration), the structural strength of the Glukhovetskii kaolin and of the Lower Cambrian clays increased, a fact that has been confirmed by our observations on the behavior of semisolid Lower Cambrian clays in a vibration-driven core barrel, both during the vibration and after the vibration had stopped. An interval of 2-3 min after cessation of vibration was sufficient for clay that had previously been very viscous (like pitch, free to flow, though slowly, from the core barrel to become dense and to lose all capacity to flow. Furthermore, the clay became so dense it required a considerable effort, and prying with a bar, to extract the clay from the barrel. A similar behavior has been noted during vibrodrilling operations in slightly plastic morainal soils and in other types of deposits.

In the second series of experiments, when a new mass of clay was introduced for the intervals of vibration for 10 and 15 min and after which the samples were "rested" for 24 hr, a greater structural strength was noted in the clays. The depth of penetration, after the day's "rest," was found to be less than the depth observed immediately after vibration.

From the above-cited data it may be seen that minerals of the montmorillonite group, i.e., minerals with mobile

lattices, have a greater capacity for thixotropic transformation than minerals of the kaolinite or hydromica groups, of which hydromicas have a greater capacity than minerals in the kaolinite group. This means that the capacity for thixotropic transformation is associated with the structure of the crystalline lattices of the colloidally dispersed minerals, since some of these are mobile, some are not. From this it follows that the conditions mentioned in § 5 for the mutual relations between thixotropy of soils and the grain size of the soils, where it was shown that clay particles must constitute at least 1-2% of the mass for thixotropy to be present, may now be stated in a more precise form. The greater the proportion of montmorillonitic particles in clayey soils, rather than kaolinitic or hydromicaceous particles, the less the total content of clay need be, other things being equal, for thixotropy to be effective in these soils.

§ 8. THE RELATIONSHIP BETWEEN THIXOTROPY IN SOILS AND THE MOISTURE AND PLASTICITY OF THE SOILS

From the data in § 1 it follows that the capacity of soils to undergo thixotropic transformations depends on the moisture content. Professor A. I. Avgustinik has shown (Fig. 15) that, for a number of clays, each type of clay is characterized by a family of curves of different slopes, depending on the moisture content. The last column in the figure shows curves for kaoline No. 1, which was subjected to electrodialysis for four hours; it is well known that the result of this process is the separation of sodium and calcium cations and the replacement of these by hydrogen ions. From Fig. 15 it may be seen that electrodialysis lowered the thixotropic effect. The relationship between thixotropic induration of various clays and the moisture content of the clays is shown in Fig. 16. This figure shows that that the general character of the indicated relationship is the same for all the clays: all the curves give a single maximum, greater for some clays, lower for others.

On the basis of these data A. I. Avgustinik has come to believe that thixotropic structure develops weakly when there is little organization moisture. With increase in moisture content, the forces controlling the development of structure mount, reaching a maximum at some optimum moisture content for each of the clays. With increase of moisture content beyond this optimum, the distance between particles increases, and there occurs a lessening of the forces controlling the development of structure; the effectiveness of the forces becomes null when the clay forms a suspension.

The investigated data do not permit the forming of adequate views concerning the relationship between the degree to which soils are capable of thixotropic transformation and the ratio of free to physically bound water. This question has been discussed by Professor N. M. Gersevanov [21], who, in establishing "necessary conditions for thixotropy in soils," in addition to those already noted above (p. 24), believes that soils "should be soil masses, i.e., should contain free water in their pores" before vibration. But, in speaking of this, Professor N. M. Gersevanov advances no proofs in favor of his view, nothing based either on experimental data or on observations. Furthermore, the data we have obtained during vibrodrilling attest to the opposite conclusion. Let us turn to a consideration of these data now.

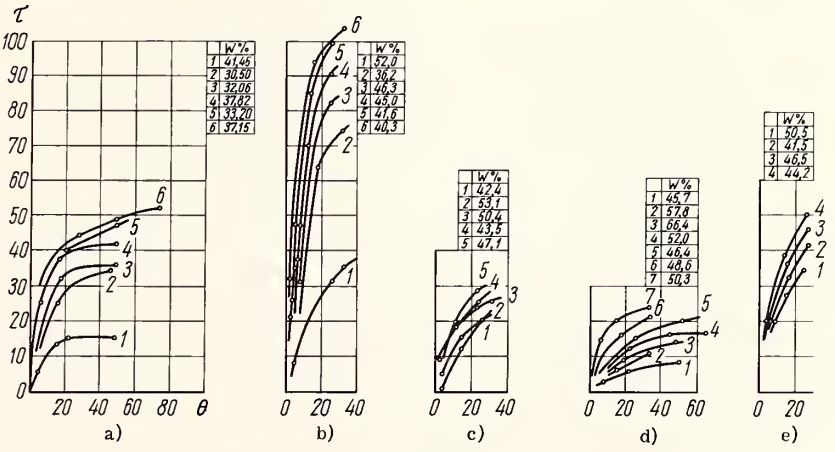


Fig. 15. Curves for thixotropic consolidation of various clays, depending on the moisture content $\tau = f(\theta)$ at constant W: a) Ryazhsk clay ρ, b) kaolin No. 1, c) Latnaya clay No. 2, d) kaolin No. 4, e) kaolin No. 1 (after 4 hours of electrodialysis).

The observations we have made concerning the behavior of clayey soils during vibrodrilling furnish a basis for believing that the softening of the soils, even their liquefaction, is associated with free water. It may be asked: Where does the water come from? Two sources are possible. As is well known, during softening and, especially, during liquefaction, the structure of a clayey soil is destroyed, the structural bonds are ruptured. This leads to

the liberation of immobilized free water from the pores of the soil. On the other hand, during vibration, physically bound water is transformed to free water; of this we are convinced by the following. It has been established by continuous desiccation [29] that all the water in the massive samples of Lower Cambrian clays that we examined was physically bound. On the other hand it has been noted that these clays flowed like viscous liquid when they were agitated in the vibrating core barrel [25]. From this it follows that physically bound water changes to free water during vibration; and this water, as our observations on the Lower Cambrian and other clays have shown, covers the surface of the soil in the cylinder with a thin film during vibration (the soil becomes glossy). This film disappears (the soil becomes dull) when the vibration stops, a phenomenon that apparently indicates a return of the water to the bound state.

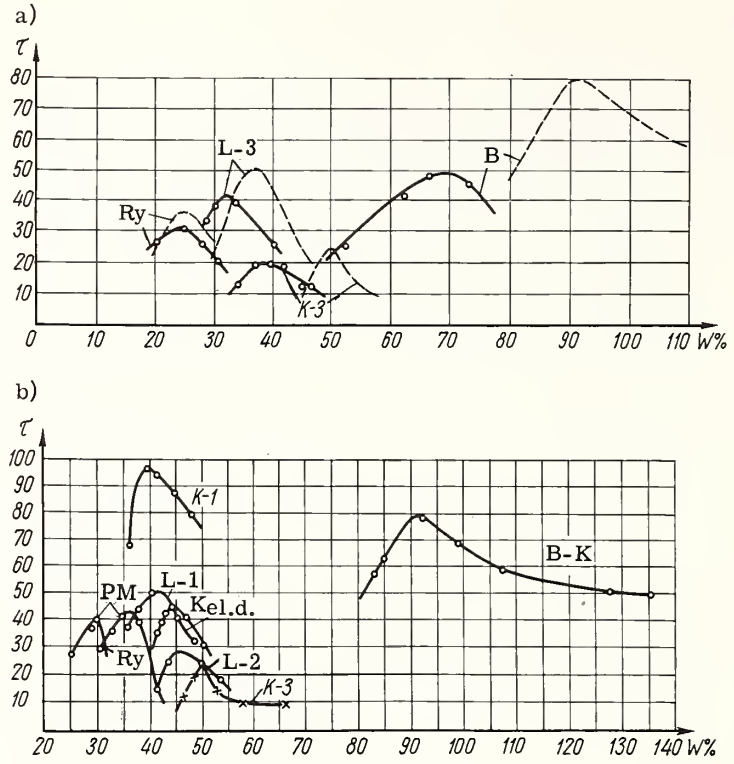


Fig. 16. The effect of moisture on the thixotropy of various clays: a) curves of thixotropic induration of clays (coagulated by aluminum sulfate) in relation to moisture content (solid lines; dashed lines refer to uncoagulated clays); Ry) Ryazhsk, yellow; L-3) Latnaya No. 3; K-3) kaolin No. 3; and B) bentonite; b) curves of thixotropic induration of a number of other clays in relation to moisture content; PM) porcelain-clay mass; L-1) Latnaya No. 1; L-2) Latnaya clay No. 2; K-1) kaolin No. 1; K-3) kaolin No. 3; $K_{el.d.}$) kaolin No. 1 after electrodialysis; B-K) bentonite from the Caucasus; B) bentonite.

Since all the water in the samples of Lower Cambrian clay was physically bound water, it may be concluded that free water prior to vibration is not absolutely necessary in order for thixotropic transformations to occur in clays. This water (as a necessary prerequisite for developing the capacity of soils to flow like a viscous liquid) appears by the transformation of physically bound water during vibration and by the liberation of immobilized free water in the cells of the soil framework when the framework is destroyed. The free water under such circumstances acts as a lubricant, lowering the resistance of the soil to shear along the walls of the vibrating core barrel, as a result of which the soil freely flows out of the barrel when it is being vibrated.

The picture here described characterizes the transition from gel to sol. The transition from sol to gel is also observed, after the vibration of clay soils has ceased, when, after the lapse of several minutes, the soils lose their capacity to flow and become somewhat consolidated; it then becomes necessary to expend considerable effort to extract them from the barrel.

The described change in physical state of soils also involves a transformation of water in the opposite direction: free water changes to physically bound water, and part is immobilized. This process, together with the interaction of particles, creates conditions for restoring the structure of the soil.

These data find support in the investigations of I. M. Gor'kova [23], who has reported that the "vibration of

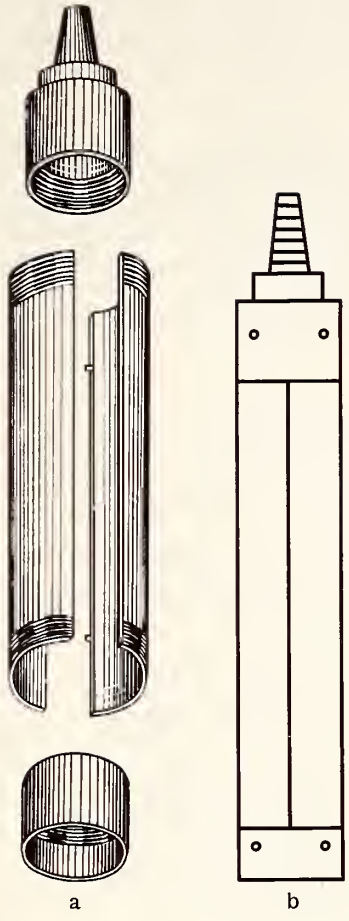
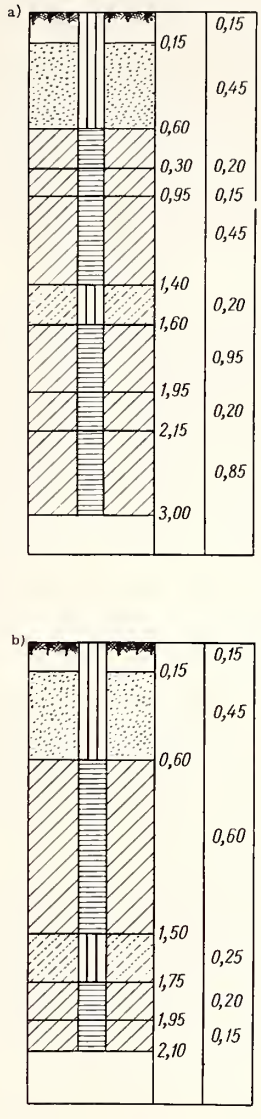


Fig. 17. Diagram of a sectional barrel: a) dismantled view, b) assembled view.

thixotropically indurated samples leads to a sharp lowering of the shearing limit, to values amounting to parts of a gram per square centimeter. But, on the cessation of vibration there is immediate restoration of the strength, corresponding to a given moisture content in the sample."



Column	Depth to base of layer, m	Thickness of layer, m	Description of rock
			Hand drilling (a)
	0,15	0,15	Soil-vegetation layer
	0,60	0,45	Sand, varigrained with pebbles and cobbles, slightly moist
	0,30	0,20	Clay, violet-red
	0,95	0,15	Clay, light blue, dense
	1,40	0,45	Clay, gray-blue, with thin layers of sand
	1,60	0,20	Sandy loam, gray-blue, micaceous, slightly moist
	1,95	0,95	Clay, gray-blue, dense
	2,15	0,20	Clay, red-brown, very dense
	3,00	0,85	Clay, pale rose, dense
			Vibrodrilling (b)
	0,15	0,15	Soil-vegetation layer
	0,60	0,45	Sand, varigrained, with inclusions of gravel and individual pebbles and cobbles, slightly moist
	1,50	0,60	Clay, gray-blue, with red-brown spots
	1,75	0,25	Sandy loam, gray-blue, moderately dense, slightly moist
	1,95	0,20	Clay, gray-blue, very dense
	2,10	0,15	Clay, red-brown, very dense

Fig. 18. Geologic columns of drill holes (after N. M. Markova). Horizontal lines show dry soil, vertical lines moist soil.

Confirmation of the above-cited opinion concerning the transformation of water types during vibrodrilling in clay soils—an opinion developed from our observations of studies in 1952—appeared in our investigations in 1953, when about ten holes were sunk at test sites by vibrodrilling. Most of the holes were drilled with a sectional barrel one meter long (Fig. 17a), consisting of two halves, which, when joined together (by a cap attachment at the top and a shoe at the base), forms a complete cylinder with an internal diameter of 102 mm (Fig. 17b).

The vibrodrilling was done in a sequence of alluvial loams and sandy loams, containing thin layers of sand and resting upon Upper Devonian clays. The sequence is shown diagrammatically in Fig. 18a and b.

On raising the sectional barrel it was found that the suspension discharged through small channels at a number of places in the vent (between the two halves of the barrel), flowing onto the outer surface (Fig. 19). In observing

Fig. 19. Water (a) flowing to the surface of the vent in the sectional barrel.

this phenomenon one gained the impression that the drilling was being done in soil completely saturated with water. But no free water was encountered in the hole. Moreover, when the barrel was extracted from the hole and opened, the soil proved to be so "dry" that no one could possibly maintain it was saturated with water. It is important to note that the discharge of suspension was observed only for material that came from one of the clay layers.

The question arises: Where did this freely flowing suspension, oozing from a number of places in the vent, come from? When we consider the above-expressed opinion concerning the freeing of immobilized water during vibration and the change of physically bound water to free water, as well as the transformation of free water to bound water when the vibration ceases, it seems to us that the very fact of suspension oozing out of the vent is complete confirmation of the expressed view. The same point of view is further strengthened by the data in Table 4, obtained at one of the test sites where the discharge of suspension through the vent of the sectional barrel was observed.

Table 4

Data on Natural Moisture Content on Soils from Vibrodrilled Holes

Sample depth, m	Natural moisture, %		Loss of water, %
	Ordinary test hole	Vibrodrilled hole	
1.05-1.10	25.10	23.50	1.60
1.15-1.20	19.60	17.90	1.70
1.25-1.30	18.65	17.75	0.90
1.35-1.40	19.65	15.20	4.45
1.45-1.47	20.30	16.00	4.30
1.55-1.60	21.30	20.80	0.50
1.65-1.69	17.40	16.70	0.70

It might be thought that, had this change from physically bound water to free water during vibration in clay soils not occurred, the natural moisture in soil samples from any particular depth where seepage of free water was observed into the ordinary and the vibrodrilled holes should be the same for both types of holes. However, it may be seen from Table 4 that the natural moisture content is considerably greater in a particular soil layer in the ordinary hole than in the vibrodrilled hole.

The question might also be raised why water did not seep out during vibrodrilling with a nonsectional barrel (Fig. 20) in those soils from which it did flow when the sectional barrel was used. The picture described above of free water discharging through the slit was not observed during drilling with the nonsectional barrel because the free water that was liberated for the above-indicated reasons could, and actually did, combine with the soil protruding through to the surface in the slit. In the sectional barrel, the free water found escape to the outside through the gap between the two halves of the barrel. This outward escape of water is shown in Table 4 by the decrease in moisture content of soils in the vibrodrilled wells.

Thus, in taking exception to N. M. Gersevanov, we note that the presence of free water in the pores of soil *before the soil can exhibit thixotropy during vibration is not at all necessary*. Soils may contain only physically bound water before vibration, as our experiments have made clear, and, despite this, thixotropy will be manifested during drilling, because of freeing immobilized water from soil pores when the structure is destroyed, on the one hand, and because of transforming physically bound water to free water, on the other. From this it follows that free water appears in the soil only during vibration, lowering the resistance of the soil to shear when the vibrating core-barrel penetrates it.

The cited data indicate that the assertions of those investigators who maintain the processes at work during vibration of clay soils are purely physical [10] are not quite precise. The processes are actually physicochemical, and the knowledge of this is of fundamental significance, since it permits us, in considering the nature of the processes, to control the processes more precisely, to develop suitable vibrator designs, and to establish proper techniques for vibrodrilling operations.

The experimental data cited and the field observations are of still further interest because they support the views of those investigators who believe that thixotropic capacity must be explained by a change in the hydrated envelopes of physically bound water contained in the pores of clayey soils, envelopes that cover fragments of crystalline lattices of minerals with varying density.

We have found support of the above-expressed views concerning the causes of easier penetration of the vibrating

core barrel during vibrodrilling in the statements of Seed and Chan [101] in regards to volcanic ash: This material, extremely difficult to compact and occurring in a dense state in the cut from which it was taken, became plastic during treatment, changing on further application to a semifluid state "with no increase in moisture."

Let us return to the design of the sectional core barrel in order to evaluate its suitability for production purposes. It is clear that when, during vibrodrilling, it is desired to obtain soil samples with moisture contents characteristic of the natural state, the sectional barrel may not be used, since it permits the discharge of suspensions during operation. This would give results showing a lower natural moisture content in wells drilled with the sectional barrel; i.e., it would indicate a higher structural evaluation than might be admissible for structural purposes. This statement is based on data kindly submitted to us by our scientific coworker in the Department of Soil Science at the Leningrad State University, G. F. Bogdanov; the data are included in Table 5 and show the results of experiments on determining the compaction curves of a number of soil samples with undisturbed structure.

It may be seen from Table 5 that an increase in pressure of 1-2 kg/cm² produces a decrease in moisture content of 1.5-2.5%, i.e., the difference in moisture content observed when drilling with the sectional and with the nonsectional barrel (Table 4). If the pressure is increased to 3-5 kg/cm², the decrease in moisture amounts to 4-5%.

Professor Boswell [94] has approached the important question concerning the relationship between thixotropy of soils and the moisture content in a somewhat different way; he has used for this purpose data on liquid limit and some other data (Table 6).

From Table 6 it is seen that the thixotropy of soils apparently increases not only with the liquid limit but also with the plasticity index, if we keep in mind the meaning of the values N and UTV.* Unfortunately the cited data for establishing some particular quantitative relationship (limit) are still very meager, and our obvious task should be to accumulate more of such data.

Fig. 20. Nonsectional barrel.

Table 5

Data on the Determination of Compaction Curves for Certain Soils

Sample No.	Type of soil	Consistency of soil before experiment	Age	Depth to sampled horizon, m	Natural moisture content before experiment, W_e, %	Moisture (W), in %, and porosity (ϵ) at indicated pressures, in kg/cm²							
						1.0		2.0		3.0		5.0	
						W	ϵ	W	ϵ	W	ϵ	W	ϵ
1	Loam, heavy, silty	Soft-plastic	Quaternary	15.3-15.7	25.8	24.34	0.662	23.37	0.645	22.93	0.633	22.31	0.616
2	Clay, silty	Soft-plastic	Quaternary	17.0	16.9	16.46	0.725	25.73	0.705	25.21	0.691	22.08	0.605

Apparently a more sensitive characteristic (than liquid limit) of the capacity of a soil for thixotropic transformation is the liquid index K_m, since its computation involves the lower liquid limit, the limit of plastic flow in the tube, and, principally, the natural moisture content. However, because of inadequate data, it is premature in this case also to make any generalizations.

In direct connection with the problem of the kinds of water in soils and the manifestation of thixotropy in soils stands the question of minimum moisture at which clay soils are able to become viscous during vibration (in

* Translator's note: N signifies void ratio of a system which just does not flow when the tube is inverted after one minute's rest, but which does flow freely if a slight tap is given to it. Numerically it is the ratio of volume of liquid to volume of solid. UTV (given as UFV in the Russian text) signifies upper thixotropic value, and is measured after the material has rested several days.

Table 6

Characteristics of Various Clays

Sample No.	Name of soil	Natural moisture content, W, %	Lower liquid limit, W_m, %	Plasticity limit, W_p, %	Plasticity index, $W_m - W_p$, ϕ, %	Liquid index, K_m, ** %	Density, Δ, g/cm³	Compressive strength, P,* kg/cm²	Thixotropic values expressed in g of water per 100 g of soil after:	
									one minute's rest, N	a rest of several days, UTV
1	Weathered clay (Gault) . .	28.2	83.3	23.8	59.5	0.07	2.67	2.3	110	140
2	The same	27.8	82.2	18.5	63.7	0.15	2.69	2.7	120	128
3	Senonian chalk	—	22.7	18.8	3.9	—	2.72	—	48	56
4	Clay from the Reading beds	12.5	37.0	12.6	24.4	—	2.62	6.6	52	76
5	London clay	22.2	57.9	18.2	39.7	0.10	2.66	4.2	61	85
6	The same	25.2	74.8	20.9	53.9	0.08	2.67	2.3	100	105
7	"	26.3	82.1	22.9	59.2	0.06	2.68	1.9	140	210
8	"	18.8	55.5	16.6	38.9	0.06	2.61	3.6	90	140
9	"	21.5	50.0	16.7	33.3	0.14	2.68	3.5	65	100
10	"	26.9	44.8	17.6	27.2	0.34	2.75	5.4	60	70
11	"	23.5	47.9	22.3	25.6	0.05	2.72	2.6	85	125
12	"	26.8	75.5	20.1	55.4	0.12	2.71	2.2	100	170
13	"	22.3	58.1	19.7	38.4	0.07	2.74	5.9	110	—
14	"	28.1	78.2	21.9	56.3	0.11	2.67	1.3	132	156
15	"	25.7	71.8	19.5	52.3	0.12	2.73	2.4	120	140
16	"	26.7	75.0	21.4	53.6	0.10	2.76	2.0	100	160
17	"	25.5	46.5	16.0	30.5	0.32	—	—	65	85
18	Clay from the Bracklesham beds	28.9	45.7	18.0	27.7	0.39	2.62	—	55	90
19	The same	28.8	44.7	17.5	27.2	0.42	2.61	—	43	70
20	Calcareous boulder clay (weathered)	16.8	42.0	13.5	28.5	0.12	2.63	4.1	70	—
21	The same	16.1	52.9	18.3	34.6	—	2.44	8.1	92	108

Explanation: * Compressive strength was determined by a confined triaxial test at 30 lb/in² lateral pressure.

** The liquid number was determined by the formula $K_m = W \frac{W_p}{\phi}$.

various degrees), i.e., at which they become thixotropic. The literature contains almost no data on the quantity of physically bound or free water; and this quantity determines the capacity of clays to flow during any particular mechanical activity to which they are subjected. There is only the note by the authors of the present book [25] to the effect that semisolid Lower Cambrian clays at Leningrad softened during drilling, changing to a viscous liquid state, and that the total natural moisture content was 14.22% (almost entirely physically bound).

We have encountered an interesting statement concerning the indicated question by N. M. Gersevanov [21], in which one of the necessary conditions of thixotropy, in addition to those already mentioned, is considered to be: "the moisture content must be greater than the plastic limit." This statement is accompanied by the following note: "if, for example, the moisture content W does not exceed the maximum molecular moisture capacity W_{mmm}, we may state that the soil is not thixotropic."

To explain the validity of this point of view let us turn to the data on moisture content of soils subjected to vibration during drilling: plastic limits, natural moisture contents, and other characteristics (see Table 3).

From Table 3 it may be seen that the position of N. M. Gersevanov is far from being justified in all cases, since a number of data show the natural moisture content to be less than the plastic limit in the tube and yet the soils represented by these values became viscous during vibrodrilling. The values for plastic limits in this table were obtained for air-dried samples. When we consider that some colloids in clay soils partially coagulate irreversibly during desiccation, it means that the data in Table 3 on plastic limits are to some extent too low. In other words, should the plastic limits be measured in samples with natural moisture contents, the numerical values would be

greater. This statement is confirmed by the data in Table 7, from which it may be seen that in all cases when the lower liquid limit and the plastic limit in the tube were measured for samples of clay with natural moisture content, the values proved to be much higher than for air-dried samples.

A comparison of the natural moisture content with the maximum molecular moisture capacity gives a different picture. In this case, the condition stipulated by N. M. Gersevanov is completely satisfied. However, when we consider that the W_{mmm} of soils is not the boundary between free water and physically bound water (and many investigators have now proved that it is not [30a, 32, 37]), the question immediately arises whether W_{mmm} may serve as an indicator of the thixotropic capacity of soils. It seems to us that it cannot.

Table 7

Data on the Plastic Limits of Certain Clays

Clay	Mineral composition	Lower liquid limit, W_m, %		Plastic limit in the tube, W_p, %	
		State of sample			
		air-dried	with natural moisture	air-dried	with natural moisture
Lower Cambrian	Hydromicas	36.67	42.18	15.65	21.05
Upper Devonian, red	Hydromicas and beidellite	25.63	31.87	13.76	16.95
Upper Devonian, light blue	Ditto	25.85	32.26	14.29	17.74
Quaternary, banded	Hydromicas	21.45	34.24	15.12	22.19

The data in Table 3 also allow us to state that quantitatively W_{mmm} and the plastic limit W_p in the tube differ from each other in many cases; this fact casts doubt on the correctness of the views of those investigators who consider W_{mmm} and W_p, as indicators of soil properties, to be "equivalent" to each other.

Obviously this matter is not fully circumscribed by whether or not the natural moisture content of a soil corresponds to its plastic limit in the tube; it all reduces to the problem of what conditions are favorable for the manifestation of thixotropy and what are the factors that produce it. On the basis of a comparison of observations on vibrodrilling in 1952 with the BT-6 vibrator and of observations in 1953 when the VPM-1 vibrator (of somewhat different design) was used, it may be said that the moot question is strongly affected by the type of vibration and, especially, by the design of the vibrator. Thus, in one of the holes drilled with a vibrator in 1952 a weak clayey marl was encountered (Fig. 21). The barrel penetrated this material very slowly. In 1953 marl was also encountered in one of the vibeodrilled holes, but it was stronger, somewhat silicified. But it also was drilled through, and this must clearly be explained by the difference in penetrating capacity of the vibrators: the penetration was greater with the VPM-1 vibrator than with the BT-6 vibrator.

With due consideration to what has been said and on the basis of observations during vibrodrilling in soils and of data on the natural moisture in these soils (as shown in Table 3), it seems to us that clayey soils may pass into a viscous state (to some degree) at some minimal value of natural moisture when the mass is vibrated; this state permits the penetration of vibrating devices into the soil at a rate that depends on the proper design of the vibrator and the proper schedule of operation.

Apparently this problem has an analogy in the capacity of clayey soils to swell. It is well known that there are no nonswelling clayey soils; the entire question concerning the degree of swelling depends on a number of conditions. Among these conditions, as is well known, the chief ones have to do with peculiarities of the environment in which the soils are found and with the factors affecting this environment (moisture, freezing, etc.).

From Table 3 one may also discover the degree of saturation with water during vibrodrilling. It may be seen from the table that the coefficient of saturation is less than 1 for a number of clays. Consequently, the softening and liquefaction of clays may take place during vibration only if the clays represent a three-phase system, despite the extreme compactness of the clays, as was true particularly for the material from the moraine (γ = 2.1-2.15 g/cm^3).

In the light of this problem, the following data, obtained during vibrodrilling in clayey soils, are of special interest. One hole, drilled by hand (see Fig. 18a), was sunk on a terrace where a sequence of Upper Devonian beds underlay the alluvium. This hole, drilled with a 4-in. assembly, exposed a sequence of very dense, low-moisture clays of various colors, alternating, not only with each other, but also with thin seams of sand. During the drilling the density, particularly of a pale rose clay, was so great that all attempts to sink the core barrel into this clay at any satisfactory rate were unsuccessful. Some idea of the density of this clay may be obtained from indirect data. A gray-blue clay overlying the pale rose clay had a density of 2.05 g/cm^3 and a natural moisture content of 20.45%,

Fig. 21. Core of clayey marl, drilled with a vibrator.

and the coring device penetrated it. The moisture content of gray-blue sandy loam proved to be 18.4%.

Since the attempt to use an ordinary sampler in the Devonian clays was unsuccessful, a hole was started by vibrodrilling 50 cm from the hand-drilled hole. The core barrel driven by a VPM-1 vibrator penetrated 2.1 m into the clay in 7-8 min, whereas it would have taken at least 2-3 hr to penetrate to this depth by hand drilling. This comparison not only points up the possibilities of vibrodrilling and its superiority over hand drilling, but it also indicates the limits of application of vibrodrilling, because of peculiarities in the soils, above all because of the content of natural moisture (see Fig. 18b).

§ 9. THE RELATIONSHIP BETWEEN THIXOTROPY IN SOILS AND BOTH THE TYPE OF BASE EXCHANGE AND THE ADDITION OF VARIOUS ACTIVE SUBSTANCES

In the literature there is very little information on the relationship between type of base exchange in soils and the capacity of these soils for thixotropic transformations. In particular, the information we have found came from the paper of A. I. Avgustinik [3], who exposed completely saturated bentonite (from western Georgia), Latnaya clay, and Glukhovetskii kaolin to ions of Na, K, Ca, and Al. The thixotropy of the saturated clays was investigated by the penetration of a ball "as a function of the moisture content of the clays." The results of these tests are shown in Fig. 22, where the relationship between thixotropic induration (ordinate) is plotted against the moisture content of the clays (abscissa). For comparison this figure also shows similar curves (for fat clays) for the same clays in the natural state, i.e., not impregnated with cations.

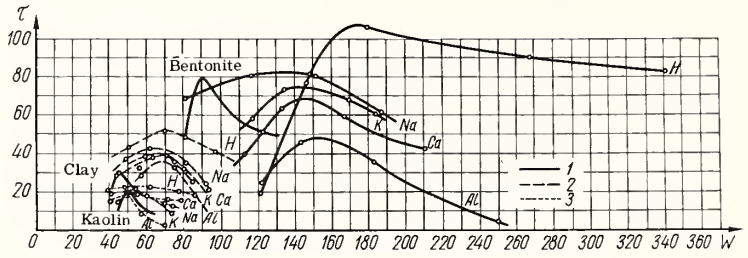


Fig. 22. The effect of ions on the thixotropy of clays: 1) bentonite from the Caucasus, 2) Latnaya clay No. 2, 3) Glukhovetskii kaolin.

An analysis of these curves shows that the relative effects of cations on thixotropic induration on the investigated clays are arranged in the following series: H > Na > K > Ca > Al; i.e., Al produces the smallest, though still rather marked, effect.

According to Boswell's data [94], the capacity for thixotropic transformations in clay soils "increases with increase in capacity for base exchange," as reflected in Table 8.

Table 8

Thixotropic Capacity of Clays in Relation to Exchange Capacity

Name of clay mineral or clay	Thixotropic limits	Exchange capacity in milliequivalents per 100 g of material
Kaolinite	70-95	3-15
Minerals intermediate in shape between kaolinite and halloysite	100-120	—
Halloysite	80-100	6-20 (and possibly greater)
Illitic clays	110-170	20-40
Beidellitic clays	170-250	—
Palygorskitic (attapulgitic) clays	530	25-30
Montmorillonitic clays	700-1350	60-100

It is known that the different types of physically bound water exhibit differences in strength of bonds with the micelle nucleus. From this it follows that the softening and, even more, the liquefaction of clayey soils during vibrodrilling signifies a weakening, even a nullification, of these bonds.

Thus, in those cases when further penetration of the vibrator-driven barrel (or piling) proves to be impossible in clayey soils, it becomes necessary to employ some technique to destroy these bonds.

As is well known, one such technique involves the use of electrolytes, which, depending on their composition, act variously to alter the properties of the soil. The data of V. S. Sharov [87], shown in Table 9, bear witness to this fact.

Table 9

The Quantity of Water Imbibed during Free Swelling of Bentonite Impregnated with Various Cations

	Li	Na	K	Mg	Ca	Sr	H
		Bentonites					
Quantity of bound water, %	1175.6	1054.2	223.4	119.4	99.4	95.4	113.6

It may be seen from Table 9 that the indicated pattern is subject to the lyotropic series of ions; i.e., the ions are arranged according to increasing energy of hydration, the property that determines their place in exchange reactions.

It is very important to civil engineers to systematize the information on what reagents (substances) and what concentrations increase or decrease the thixotropic capacities of soils under conditions of natural moisture content. The importance of this question for practical purposes is even further heightened by the fact that, under certain circumstances, a sol may be converted to a gel, with the well-defined properties of a solid body, by the addition of negligible quantities of some particular substance. Thus, according to Russel and Rideal [98, 100], it is sufficient to add one part of a solution of Al_2O_3 to 4000 parts of quartz sand with diameters from 0.02 to 0.16 mm for thixotropic consolidation to be produced in the particles. Russel obtained the same results with natural clay. The particles of the suspension are found to be covered with the colloidally dispersed substance in the form of a protective film. The colloids were almost completely separated by repeated contrifuging and by subsequent peptization in fresh solution. The capacity of clay for thixotropic gelatinization was lost in this process.

Interesting data have been furnished by S. E. Bresler [17], who has reported that it is sufficient to add a small quantity of material with long-chain molecules to nonthixotropic systems for the latter to acquire well-defined thixotropic properties. These data have been confirmed by the investigations of I. M. Gor'kova [23], who has succeeded in showing that in true quicksands, "in contrast to pure sands, the presence of highly dispersed mineral particles and chain molecules of humic acids imparts well-defined thixotropic properties to the sandy-colloidal rock."

In the light of this problem it is also of interest to note the statement of H. Freundlich [82] that a suspension of kaolin may be made thixotropic by the addition, not of pure water, but of a solution of alkalies.

Among the active additives for soils there is special interest in those that play a definite role in geologic processes. Professor Boswell [93], in studying the effect of additions of silica and soda on the properties of the soil, has pointed out that electrolytes arising during the hydrolysis of water glass (sodium silicate) in weak solutions exhibit the greatest effect on producing thixotropy in fat clays, less effect in lean clays, and the least effect in clay-poor or ferruginous sediments.

The same author has shown that such substances as silica and soda are also important agents in increasing the thixotropic capacity of soils. Corresponding experiments with colloidal silica and sodium hydroxide have shown that, in comparable concentrations, each reagent may increase this capacity, but the effect is generally less than the effect of water glass. Experiments have revealed that the addition of silica in quantities not exceeding 2% (by weight) of the total weight of the system produces no marked change in thixotropic capacity. But silica when added in quantities 2-3% the total weight has proved to have a noticeable effect.

A very important statement has also been made by Kiffer [82] concerning the effect of changing ratios of alkalies and silicic acids in water glass on the liquefaction of ceramic (clay) materials. Here the effect of water glass on kaolin and clay is not the same as the effect of soda and alkalies, because the latter act only as liquefying media, whereas silicic acid, forming from the decomposition of water glass, acts as a protective colloid,* and the alkali

* In colloidal chemistry a protective colloid is one that imparts stability to hydrophobic sols by changes on the surfaces of the particles, involving an adsorbed layer of hydrophilic, highly dispersed sol.

in combination with them liquefies the clay in enhanced degree. Consequently, the more SiO_2 in the ratio Na_2O : SiO_2, the earlier the optimum liquefaction is attained.

Thus, the addition of water glass in a definite concentration to soil may increase its thixotropic capacity, and the soil becomes more hydrophilic. This phenomenon has been confirmed by an experiment in drilling oil wells by the "Association of the Saratov Petroleum Industry," where the foreman of one of the drilling crews, Mr. Christoforov, used water glass as drilling fluid, and this practice increased the drilling rate of the crew by a factor of 6.5. By drilling with water glass the crew sank a hole to a depth of 1600 n in 26 days, instead of 58 days as planned; the cost of drilling was thus cut in half.

In considering the addition of such active substances as electrolytes one should not forget that, depending on the concentrations, these substances may act as peptizers, keeping the particles in a suspended state, or as flocculants, tending to flocculate the particles. In other words, our concern is only with definite concentrations of electrolytes that will increase the thixotropic capacity. For example, according to Pryce-Jones, a concentration of 0.5% sodium silicate causes thixotropy and a concentration of 0.1% causes peptization in a system composed of 5% bentonite.

The data of Winkler [99] is important also; this writer has stated that there is a "decrease in thixotropy in montmorillonite on the addition of such electrolytes as NaCl, KCl, NaOH, and KOH in concentrations that produce an increase in thixotropy in kaolinite and most other clays as well as in pulverized minerals."

According to H. Freundlich [82], who worked with thoroughly electrodialyzed bentonites (the electrodialysis was carried out for 8 days), a decrease in thixotropy was found, the degree depending on the valence of the electrolyte introduced into the soil: barium and calcium had less effect than sodium and potassium; aluminum and quadrivalent thorium displayed no effect on thixotropy.

The coagulation capacity of the electrolytes also proves to be very effective in modifying the rate of thixotropic consolidation. One may find indications of this in the literature, to the effect that hydrous aluminum oxides, when present in quantities of 12.16 g/liter, decrease the time required for gelatinization from 4 hr to 28 sec when the concentration of the electrolyte NaCl is increased from 0.2 mole/liter to 0.375 mole/liter [43].

In considering the additions of substances that impart to soils a capacity for thixotropic transformation it is of interest to note the views of ceramic engineers. In this regard Professor A. S. Berkman and A. I. Miklashevskii, a candidate in the chemical sciences, have written: "A rather small admixture of thixotropic material that cannot be washed away from the clay particles may exhibit thixotropic properties throughout the entire mass; i.e., a small percent of thixotropy-imparting mixture in the system may, as it were, induce thixotropic properties in the entire mass" [15].

Organic colloids in soils are frequently found to have a considerable effect on producing thixotropy in soils. If we consider that clayey soils, particularly soils in the agricultural sense, contain many colloidal organic substances and have high liquid limits, then, in keeping with the above-noted relationship between thixotropy and liquid limits, it becomes clear that the addition of these organic substances also increases thixotropy. The above-cited statement of I. M. Gor'kova concerning this matter is confirmation. Boswell reported [94] that, in order to increase thixotropy, he used natural organic colloids as well as various chemical products, and, despite their differences in origin, the effect obtained was the same.

The question naturally arises of means of introducing these active substances into the ground. It is clear that when the ground is massive, as is true during vibrodrilling, when sinking rods by vibration, and when driving piles, the simplest method of introducing thixotropic material is to smear the penetrating object with thixotropic paste or to douse the object with the proper solutions. Actually some doubt may arise concerning this technique, since the object will experience strong resistance from the soil along its sides as it penetrates the ground, and any material smeared on may be rubbed off during this process. However, this objection has scarcely any foundation when we take into account some data of A. A. Biryukov [16]. As his experiments have shown, in ground deformed by the driving of piling it is necessary to distinguish a number of zones, the first of which is 0.5-1 cm thick and encircles the pile, including the tip, with a dense envelope in the form of a "jacket," consisting of the overlying soil pierced by and clinging to the pile.

The truth of this is confirmed by the experiments of Professor N. V. Paletin, bringing to light the formation of a dense zone of soil about the pile. These experiments "have shown that the dense zone about the pile forms only through the effect of the lower pointed tip of the pile, since, during penetration of the pile into the ground, movement of soil particles is observed only within a certain zone adjacent to the lower end of the pile. This zone of movement of soil particles shifts downward with the penetration of the pile, *remaining, as it were, attached to the lower end*" (italics of B. M. Gumenskii).

§ 10. THE EFFECT OF TEMPERATURE CHANGES ON THIXOTROPY IN SOILS

A. I. Avgustinik [2] has shown that an elevation in temperature speeds up thixotropic consolidation only within the range from 25 to 40° C. A higher temperature destroys "that structure of organized arrangement of water dipoles, which forms under the influence of the opposing ions found in the adsorbed and diffuse layer." In the opinion of Professor A. I. Avgustinik an elevated temperature facilites a better orientation of the molecules, up to a certain point, and this orientation makes for much greater ease in movement. Because of this, the opposing ions, acting like magnets, speed up the orientation of the dipoles. But when the amount of thermal energy exceeds some limit, this energy begins to disorient the dipolar molecules of water. These molecules, being unstable, foster the development of chaotic thermal movement, inherent in liquids at high temperatures. These data indicate that the mechanism of growth of thixotropic structures in clayey soils must be associated with layers of physically bound water.

§ 11. THE EFFECT OF ELECTROOSMOSIS ON THIXOTROPY IN SOILS

It is well known that the properties of finely dispersed soils depend on electrical forces (charges) manifested on the surfaces between soil particles and soil solutions. The greater the specific surface of the particles in the soil the greater the effect the electrical forces have on any particular property important to civil engineers.

The presence of electrical forces in clayey soils may be verified by an experiment first performed in 1808 by Professor F. F. Reiss at the Moscow University.

Professor Reiss inserted two glass tubes into a piece of untreated clay (1) (Fig. 23). After this, washed (clean) sand was poured into both tubes; water was poured over the sand, and an electrode was inserted in each tube and attached to the terminals of a galvanic cell. After some time the water in tube 2 (with the positive electrode) became turbid because of the migration of clay particles to the electrode through the layer of sand. In tube 3 (with the negative electrode) the water remained perfectly clear, but the level rose. Consequently, it may be seen that the water, like the particles of clay, did not remain immobile; they moved in a direction opposite to the movement of the clay particles, flowing across from tube 2 to tube 3. This movement of particles under the influence of an electric current has been given the name *electrophoresis (cataphoresis)*, the movement of water *electroosmosis*.

The above-cited data indicate that the charge on the clay particles was negative, since the particles moved toward the positive electrode. Water, relative to the clay particles, carried a negative charge, and this impelled them to move in the opposite direction, toward the negative electrode.

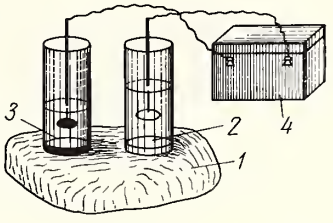


Fig. 23. Sketch of Professor Reiss's experiment: 1) untreated clay, 2) tube with positive electrode, 3) tube with negative electrode, 4) galvanic cell.

From what has been written it is clear that, electroosmosis having been produced during vibrodrilling by the passage of direct electrical current, the soil around the vibrating core barrel, which is the cathode, may pass into a plastic or even a liquid state; this possibility was confirmed by our observations in the experiment with the penetration of a cone. From the graph shown in Fig. 24 it may be seen that a cone with a weight of 116 g penetrated kaolinitic clay, under ordinary conditions, to a depth of 5.08 mm, but when direct current was applied the penetration was more than 8 mm.

The effect, no less impressive, of passing direct current through clayey soils has been discussed in the experiments of B. A. Nikolaev [102] on the sinking of piles. These experiments, performed on our recommendation, were designed to discover whether the penetration of a pile was speeded up, regardless of the method used to sink it, whenever a direct current was applied to the soil. Experiments in the laboratory and on structures where reinforced-concrete piles 50 cm in diameter were driven supported completely our views concerning the acceleration of the pile-driving process by means of electrical current; this is illustrated in Fig. 25. From Fig. 25 it may be seen that the passage of direct current speeded up the sinking of piles. The saving of time in this process amounted to 40%. Approximately the same saving of time was observed in operations on the sinking of wooden piles. Metallic piles also, 89 mm in diameter, were driven with the same beneficial effect to a depth of 2.8 m using a current at a potential of 68 v.

Let us note that the clays in which the piles were driven during the passage of direct current contained no free water; this fact has been verified by special investigations (curves were constructed for the kinetics of desiccation). From this, one may conclude that free water, which gives rise to softening and even, in some cases, liquefaction of clays, developed in this case by transformation of physically bound water and by freeing immobilized water.

These investigations are of twofold interest:

1) As is well known, until now the opinion has been held that electroosmosis is possible only in soils containing

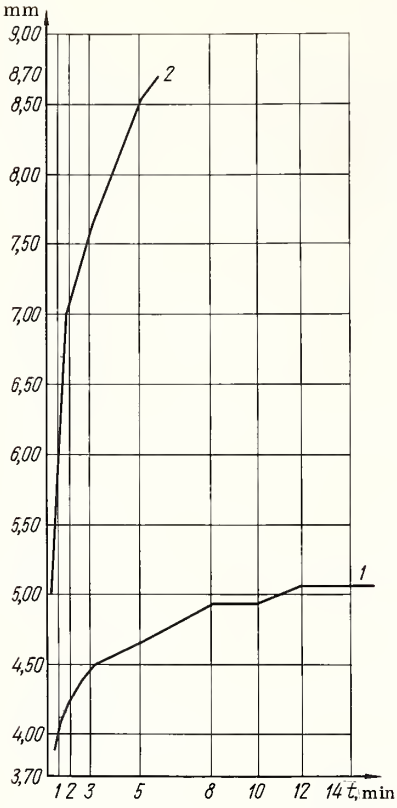


Fig. 24. Curves showing penetration of a cone into kaolinitic clay: 1) without application of direct current, 2) with applied direct current.

free water. In this connection Professor B. A. Rzhanitsyn has written [65]: "... different types of soil water apparently react differently to the passage of electrical current: hygroscopic water practically does not conduct electrical current; bound water conducts very weakly; free (gravitational) water is the principal electrically conducting medium in soils. A decrease in the amount of free water leads to a noticeable increase in the ohmic resistance of the soil." However, as shown by the data we cited above, this is not entirely true: physically bound water also conducts direct electrical current, and this behavior develops thixotropic properties in clayey soils. In order for thixotropy to develop, the vibrating barrel (during vibrodrilling) or the casing pipe (when casing a hole) must serve as an electrode. To accomplish this one of the conductors (positive) is attached to the barrel (or casing pipe) and the other conductor (negative) is led to the ground;

2) Figures 24 and 25 show that the strong impulses imparted by vibrators during drilling can hardly be considered a decisive factor in this process.

One should also recognize the nature of the effect of alternating current. There are, however, no direct data on the effect of alternating current on soils; it has been noted merely that the passage of alternating current through a thixotropic gel of iron oxide and NaCl led to solidification. After 10 hours of treating the gel the time of thixotropic consolidation decreased from 117 to 29 min. These data point up the necessity of performing corresponding experiments to test the possibility of passing alternating currents of various frequencies through the soil surrounding the pile or pipe in order to speed up induration or liquefaction.

§ 12. ULTRASONIC WAVES AS A SOURCE OF THIXOTROPIC TRANSFORMATION OF SOILS

In physical acoustics sound vibrations are divided into infrasonic (elastic oscillations with frequencies from 0 to 20 cps), audible (vibrations with frequencies from 20 to 20,000 cps), and ultrasonic (vibrations with frequencies higher than 20,000, up to frequencies of 10^8-10^9 cps). The nature of ultrasonic waves is the same as of ordinary sound waves: they may be propagated through solid, liquid, and gaseous material. Ultrasonic vibrations may be produced by mechanical, thermal, electrical, magnetostrictional, and piezoelectric emitters (quartz, tourmaline, and other materials), of which the last type yields the most powerful ultrasonic vibrations.

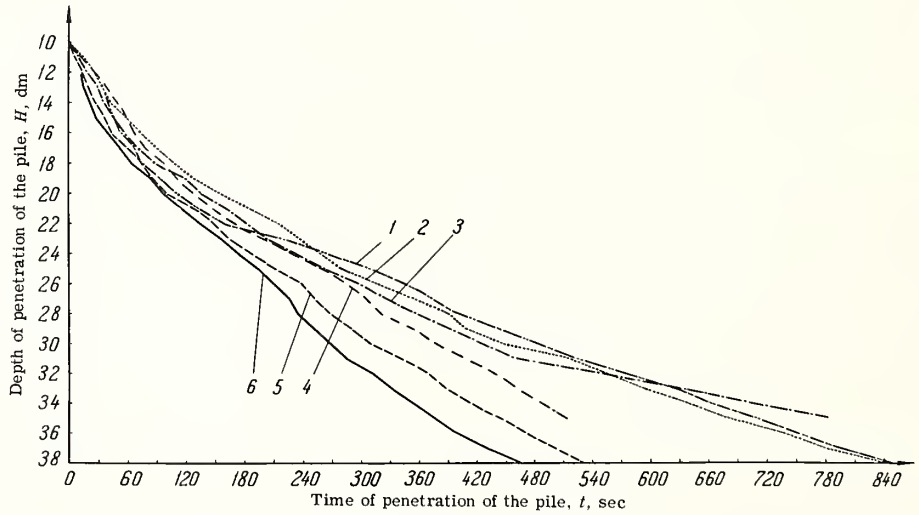


Fig. 25. Relationship between number of blows by the hammer and depth of penetration of a metallic pile: 1, 2, and 3) curves of penetration of pile without electroosmosis; 4, 5, and 6) with electroosmosis.

Ultrasonic vibrations may produce three types of effects when acting on a substance: 1) the energy may be absorbed by the body and changed from mechanical to thermal; 2) cavities may form in liquids; 3) the energy may

transmit high velocities and acceleration to the particles in the mass. For these reasons ultrasonic oscillations frequently produce extensive changes in the body through which they are propagated.

Ultrasonic waves are capable of producing a whole series of different phenomena that are of immediate concern to the civil engineer. Among these phenomena the liquefaction of thixotropic gels is of special interest. It should be noted that ultrasonic vibrations have the capacity not only to disperse a substance but also to develop the opposing activity—coagulation of various disperse systems. Because of this property, ultrasonic vibrations have been suggested for use in purifying water of contaminations.

The dispersing action of ultrasonic vibrations is shown by the capacity to liquefy thixotropic gels [82]. It may be seen from the literature [29] that when a 5-10 percent solution of gelatin in water is exposed to sound waves for a short interval of time the viscosity of the solution decreases. When the sound vibrations cease, the viscosity of the system regains its original value after some time. The transition from sol to gel in this case is explained in the following way. The gel consists of an apparently entangled mass of thread-like molecules, forming a mobile framework, within which the solvent is found. The framework remains entire so long as the acting forces are small. For this reason the gel has high viscosity. When the active forces increase sufficiently the framework is disrupted and the gel begins to flow. Cavitation,* produced by ultrasonic waves, breaks the bonds between the several macromolecules and in this way destroys the framework, which was responsible for the great viscosity of the system. These bonds are due to van der Waals forces, the equivalent energy of which ranges from 2000 to 8000 calories per mole of the binding group.

When the sound waves cease, Brownian movement leads to a restoration of the destroyed framework, and the system regains its initial viscosity.

The question arises: Is the time of solidification, in the transition from gel to sol, that occurs during excitation of ultrasonic waves the same as that for other methods of consolidating the gel?

Existing data [95] indicate that the interval of time is the same as for thixotropic transformation due to other causes, such as shaking (Table 10).

Table 10

Consolidation Time for a Number of Gels

No. of gel	Consolidation time after shaking by hand, sec	Consolidation time after subjecting to ultrasonic waves for 10 sec, sec	Consolidation time after subjecting to ultrasonic waves for 1 min, sec
1	115	117	115
2	104	105	99
3	92	95	83
4	72	74	63
5	55	59	53
6	39	34	38
7	28	29	28
8	26	27	25

From Table 10 we may discern a second interesting detail of the experiments: the time required for consolidation does not depend on the duration of the treatment with ultrasonic waves.

The authors of the indicated paper have reported that an iron-oxide gel was observed to become fluid first in the upper part, at the interface with air (the experiments were made in chemical beakers). During the experiment it was noted that the color changed in that part of the gel that became liquid. This part of the gel became darker, changing from yellowish cinnamon-brown to dark cinnamon-brown. The authors believe that this phenomenon, which they observed in tests with other gels, is in keeping with the existing views on the relationship between thixotropy and coagulation; similar color changes in gels were noted in the latter process.

In speaking of the fact that ultrasonic vibrations, under certain conditions, may effect coagulation, it should be emphasized that this faculty increases with increasing intensity of ultrasonic vibrations.

The data cited above attest to the likelihood that, under certain circumstances, ultrasonic vibrations may be used for vibrodrilling. Thus, in the U.S.A. [96], industrial models have been designed for vertical and horizontal

* By cavitation we generally mean explosive activity in liquids, arising under definite conditions that lead to the formation of voids; others consider cavitation to result from the separation of dissolved gases from liquids by ultrasonic vibrations.

drilling. Professor Converse (University of California) used infrared waves for compacting unconsolidated marine sands to cover a roadway for the movement of heavily loaded equipment.

§ 13. DIMENSIONS OF THE ZONE AFFECTED BY VIBRATION IN SOILS DURING VIBRODRILLING

In discussing the conditions under which thixotropy appears in clayey soils during vibrodrilling, it is important to know the dimensions of the zone affected. Actually, if, when sinking the core barrel into the ground by vibration the entire mass within it becomes plastic, the value of the data thus obtained for determining natural moisture W, density γ, density of solid constituents δ, porosity n, degree of water saturation g, and other soil characteristics cannot be great, because the operation destroys the textures and structures.

It should be noted that data on the question are almost nonexistent. Special investigations are necessary in order to acquire information on these characteristics. However, despite what has been said above, it may be stated that the other data of ours [28], obtained during vibrodrilling and manual drilling in soils, may throw some light on the problem. Table 11 shows the numerical values of natural moisture and other characteristics of soils, the samples of which were taken from ordinary test holes in some instances, from vibrodrilled holes in others (i.e., from the section inside a vibration-driven barrel with an inner diameter of 89 mm, at a distance 10-11 mm from the walls of the barrel).

From Table 11 it may be seen that the data on densities, porosity, and other characteristics of morainal soils, regardless of where the samples were taken (from ordinary holes or vibrodrilled holes) are very similar, in some cases identical. In our opinion this indicates that the zone in which thixotropy appears during vibrodrilling in clayey soils is small, the width apparently not exceeding a few millimeters.

The view that the zone of vibration is small is confirmed to some extent by our visual observations on the degree of moistening in the clayey soils forming the upper parts of the walls of the vibrodrilled holes (these observations were made immediately after the barrel was removed from the hole). Only at the surface was the moistening more extensive than in segments of soil away from the walls of the holes.

§ 14. SUMMARY

In summarizing the results discussed, the following conclusions may be drawn:

1. The thixotropic capacity in soils containing clay particles is due not to any single factor but to a combination. Chief of these is the presence of clay particles, especially montmorillonitic particles (i.e., more hydrophilic types), and also the presence of a certain amount of water, even if the water is physically bound.

2. The softening and liquefaction, during vibrodrilling, of soils that contain clay particles are the result of freeing immobilized water and, to a considerable degree, of transforming physically bound water to free water; this is the cause of the transition of soils from the state of a gel to the state of a sol. When the vibration ceases, the inverse process occurs; the water that had appeared is partly or completely transformed (this depends on the total amount of water in the soil) to physically bound water and, in part, to immobilized water; this process, together with interaction of the particles, creates conditions that lead to restoration of the structure of the soil. Consequently, processes that arise during vibration of clayey soils must be associated with the envelope of hydrates coating the clay particles and with disturbance of the contacts between these clay particles. This points out a course which may be followed for controlling thixotropy in soils, making thixotropy act in the direction necessary for the engineer.

3. Thixotropy in soils has been but little studied. At the same time, data now at hand indicate that thixotropic capacity may be extensively used for construction purposes. In order to extend the possibilities in this direction it is necessary to make more profound and thorough studies of the phenomena arising in soils during vibration.

4. Among the necessary conditions for the manifestation of thixotropy in clayey soils during vibration, the following must be considered:

a) The soils should contain at least 1.5-2.0% of particles smaller than 0.002 mm in diameter. The more material of this size contained in the soil, the more favorable will the conditions be for liquefaction; liquefaction will appear more quickly if the clay particles are colloidally dispersed minerals of the montmorillonite group rather than of kaolinite or hydromica;

b) the soils must contain a certain amount of water, which may be physically bound; it need not be free water, but it must become free during the vibration;

c) the conditions that the soil should contain no noticeable quantity of particles coarser than 0.01 mm and that the natural moisture content should not exceed the plastic limit were not always supported by the experiments, and, for this reason, they are not considered obligatory;

Table 11

Some Data on the Physical Properties of Clayey Soils with Various Grain-Size Distributions

Source	Depth at which sample was taken, m	Grain size: Content (%) of fractions of various dimensions (mm)									Type of soil	Physical state (from field observations)	Natural moisture, W, %	Density, γ, g/cm³	Density of solid constituents, δ, g/cm³	Porosity, n, %	Degree of water saturation, g, %
		>2	2-1	1-0.5	0.5-0.25	0.25-0.05	0.05-0.01	0.01--0.002	0.002--0.001	<0.001							
Vs-1	3.75-3.85	1.7	1.5	2.2	2.2	41.0	22.0	16.5	3.8	9.1	Light loam	Plastic	13.69	2.13	1.87	31.1	0.82
Vs-2	3.75-3.85	1.2	1.4	0.3	5.2	36.0	22.7	17.4	4.9	10.9	Medium loam	"	15.84	2.17	1.88	30.7	0.93
Sh-1	3.75-3.85	5.5	1.7	0.5	5.3	30.6	23.2	18.4	6.0	9.8	Ditto	"	16.02	2.07	1.79	34.45	0.82
Vs-1	4.05-4.10	2.4	1.8	2.4	4.3	33.5	23.2	18.2	4.9	9.3	Light loam	Slightly plastic	15.39	2.20	1.90	30.25	0.96
Sh-1	4.05-4.15	0.3	1.5	2.8	5.0	37.2	23.5	18.1	3.4	8.2	Ditto	Plastic	13.57	2.07	1.82	32.90	0.74
Vs-1	4.60-4.70	1.3	1.7	0.4	3.6	36.1	22.6	19.8	4.0	10.5	"	Slightly plastic	—	—	—	—	—
Vs-1	5.00-5.10	1.0	1.0	3.2	4.1	34.6	23.7	18.9	4.3	9.2	"	Ditto	14.21	2.12	1.85	31.8	0.86
Sh-1	5.00-5.10	2.2	2.0	3.2	5.0	27.0	25.8	23.9	2.0	8.9	"	Plastic	14.21	2.18	1.86	30.55	0.91
Vs-1	5.50-5.55	3.9	2.1	3.1	5.4	30.6	20.4	20.0	4.7	9.8	"	Slightly plastic	11.86	2.25	2.02	26.5	0.90
Sh-1	5.50-5.55	2.2	1.9	3.2	5.2	27.5	25.6	21.5	4.5	8.4	Light loam	Plastic	13.86	2.15	1.90	30.6	0.85
Vs-3	1.35-1.40	—	—	0.3	2.8	56.2	15.0	9.7	4.9	11.1	Medium loam	Dense, dry	21.61	2.07	1.70	37.27	0.96
Sh-2	1.35-1.40	—	—	0.1	2.2	58.3	11.6	10.7	3.2	13.9	Ditto	Ditto	19.98	2.03	1.69	36.3	0.92
Vs-3a	2.20-2.25	Individual grains	—	0.3	5.9	65.8	16.2	3.7	1.1	7.0	Sandy loam, heavy	Plastic	13.26	2.07	1.78	34.32	0.67
Sh-2	2.20-2.25	—	0.2	0.9	15.9	58.9	12.0	5.7	0.9	5.5	Ditto	Moderately dense, dry	12.15	1.84	1.64	38.6	0.51
Vs-3a	2.50-2.55	—	1.0	0.5	14.0	72.1	7.6	1.2	1.6	2.0	Sandy loam, light	Moderately dense	6.32	1.64	1.55	41.73	0.53
Sh-2	2.50-2.55	—	0.9	0.9	15.0	73.1	5.9	1.7	0.7	1.8	Sand	Ditto	6.46	1.66	1.55	41.8	0.24
Sh-1	4.60-4.70	2.1	1.9	2.8	5.4	22.2	26.8	20.4	5.1	7.3	Light loam	Plastic	—	—	—	—	—

Explanation: Vs) vibrodrilled hole; Sh) ordinary test hole.

d) at the same time, the lower liquid limit may apparently serve as an indicator of the thixotropic capacity of soils; the higher this limit the greater the capacity of a soil to liquefy;

e) thixotropy appears in soils even when the coefficient of water saturation, g, before vibration amounts to only 0.4-0.5.

5. The possibility of clayey soils liquefying during vibrodrilling, apart from the factors noted above, depends also to a considerable extent on the penetrating capacity of the vibrator and the schedule of its operation.

6. The dimensions of the zone within which liquefaction occurs in clayey soils during vibrodrilling are apparently very small, the width hardly exceeding several millimeters.

7. The phenomenon of liquefaction may be produced by sending direct current through the soil. Apparently ultrasonic waves are actually being used for this purpose. This problem should be worked out in detail in the near future.

8. The use of active reagents as media by which liquefaction of the soil may be obtained or by which this process may be prevented may apparently open up great possibilities to construction engineers; it may also furnish greater possibilities for the conscious control of processes originating in soils.

Chapter III

VIBRODRILLING EQUIPMENT AND ITS USE IN THE EXAMINATION OF SOILS*

§ 15. THE PRINCIPAL ARRANGEMENT USED IN THE VIBRODRILLING OF SOILS

The constituent elements of any vibrodrilling outfit are: a vibrator with a directional effect of some particular design and with a head for attaching the operating drill bit or rod, a motor, and fittings for drilling (rod, adapter). Because of the considerable weight of the vibrator, a necessary piece of equipment for drilling is a hoist to raise and lower the drilling device and the attached vibrator.

The motor is attached directly to the vibrator. The drive from the motor to the shaft of the vibrator is effected by means of a V-shaped belt or by reducing gears. The motor and vibrator thus form a single unit with the head—a "vibrosinker."

The vibrosinker is connected through the head with the drilling rods or pipes, which have some particular kind of adapter at the other end. By means of shackle, hook, pulley, and cable, attached to some hoisting device, the entire system may be raised and placed in a vertical position. A general view of a vibrodrilling rig is shown in Fig. 1.

During operation of the motor the shaft of the vibrator is rotated through eccentrics mounted on it and a disturbing force is created. Because the number of eccentrics is even the horizontal forces mutually balance each other and only a vertical disturbing force is created.

The oscillations of the vibrator are transmitted by the attached drilling rod to the drill bit. When the vertical position of the drilling instrument is free, i.e., when the cable is loose and the drill bit rests on the ground, the bit sinks into the ground because of the vibration and the weight of the entire vibrosinker.

Relatively easy penetration by the drilling instrument into the ground is due to a considerable decrease in friction between the sides of the drill bit and the adjacent ground. The essence of this phenomenon is fundamentally different for vibrations in sandy and clayey soils, as appears from the data of Chapters I and II. During vibration in sands only the bond between particles is broken; the sands acquire something of a suspended character, and this facilitates the penetration of the drill bit into the ground. In clayey soils, because of their cohesion, the vibration of particles themselves, such as is observed in sands, is difficult, but the vibration destroys the diffused envelopes.

Molecules of water surrounding the soil particles and clinging to these particles by elestrostatic forces are disoriented by the vibration, and, as a consequence, part of the physically bound water is liberated. In addition, immobilized water is also set free. The presence of suspensions between the sides of the drill bit and the soil furnishes a kind of "lubricant," and this permits easier penetration of the drilling instrument into the ground. As we have shown above, this phenomenon represents one of the stages of thixotropic transformation of clayey soils.

After the drill has penetrated to the required depth the instrument is raised and a record is made of the drilled interval by collecting necessary soil samples. The final cleaning of the drill tip may be accomplished (after the logging and collection of samples) by vibrating the suspended bit. After this, the process of penetration and raising the instrument is repeated. When it is necessary to reinforce the walls of the hole with casing, the pipe is easily driven or raised by means of vibration.

To effect this operation the upper part of the pipe has a connection to which the vibrator may be attached. The oscillations of the vibrator are transmitted to the pipe and it is easily driven into the hole. At times it is necessary to lower both the drill bit and the casing (see below). The pipe is also raised by vibrating it. While the pipe is

* Please note that an explanation of the many abbreviations of names of organizations and institutes used in this chapter appear at the end of the chapter.

Table

Characteristics of the Principal Types of Vibrators Used

Type of vibrator	Motor		Weight of vibrator, gross and when vibrating	Parameters		
	Kind	Power, kw		Moment of the eccentrics, kg/cm	Vibrations per minute	Disturbing force, tons
						Vibrators with
BT-6	Electric	3.5	150/150	50	2500	3.5
BT-6	Flexible shaft from truck	3.5	190/190	50	2500	3.5
BT-9	Electric	5.8	400/400	100	2500	7.0
BT-9 (reinforced)	Ditto	5.8	400/400	200	1250	3.5
V-109	"	7.0	250/250	250-125	1250-2500	4.35-8.7
Dual	Two electric motors	2 × 2.8	370/370	300	1250	5.25
						Vibrators with
VPM-1	Electric	3.7	150/50	15-60	1500	0.4-1.5
VPM-1 (1953 model)	Ditto	4.5	175/50	15-60	1500	0.4-1.5
VPM-2	"	7.0	330/115	38-150	1550-1850	4.00-5.70
VPL-2	Benzene motor	4.4	500/200	100	1650	3.0
VBL-3	Ditto	5.2	300/100	150	1650	4.5

being vibrated it is raised by means of a cable hoist or a crane. Vibration of the string of pipe sharply decreases the friction between the pipe and the walls of the hole, and the pipe is consequently raised much more easily.

This describes the general scheme of operation of a vibrodrilling rig, and explains the general technological process. Several variations of the proposed scheme may be used according to the constructional design of the rig.

At present more than ten vibrator designs have been manufactured for use in geological exploration. Characteristics of the most widely used are shown in Table 12.

§ 16. EXISTING DESIGNS OF VIBRODRILLING EQUIPMENT

a) *Drilling Equipment Designed by Minmashstroi.* The first vibrodrilling operations were conducted on the initiative of, and in consultation with, Professor D. D. Barkan [7] in 1950 at one of the construction areas, where 150 holes were drilled to a depth of 6.5 m by means of vibrodrilling.

The raising and lowering of the vibrating system and the attached drilling device were effected by a "Yanvarets" truck-mounted crane with a load capacity of three tons (Fig. 26). The jib of the crane permitted the drilling device to be raised and lowered for a length of 6 m with no increment to the rod. The mobile crane and the shallow depth planned for the holes made it possible to use a drill equal in length to the depth of the holes and to drill each hole with a single penetration of one rod. The bit was a special point of angular iron; above this was attached ordinary metal pipe with a longitudinal slit. It was discovered during operation that the wider the slit the more easily the soil entered the pipe, and vice versa. At the same time it was observed that as the slit was increased in width it became increasingly difficult to hold the soil in the pipe. It was ascertained that sands were held satisfactorily when the width of the slit corresponded to an arc of 120°; with a wider slit sandy soils were not held. The optimum width of the slit for clayey soils proved to correspond to an arc of 160°.

A BT-6 vibrator was used to sink the drilling apparatus; it was activated by an electric motor with a speed up to 2500 rpm and a vertical disturbing force (thrust) of three tons. The weight of the vibrator and the motor was about 150 kg.

for Exploratory Drilling in Geology (after M. G. Efremov)

Amplitude of vibration (mm) at length of drill pipe (m)		Dimensions, mm		Organization that designed the vibrator	Remarks
10	20	Height	Cross section		
rigidly attached motor					
2.10	1.65	770	428 × 410	VNII for Footings and Foundations, 1949	In use
1.70	1.30	550	320 × 670	Lengiprorechtrans, 1957	"
2.05	1.80	1200	700 × 470	VNII for Footings and Foundations, 1950	"
4.10	3.60	1200	700 × 470	VNII for Footings and Foundations, 1952	"
7.50-3.75	6.20 3.10	900	540 × 530	Giprosel'élektro, 1953	Projected
6.10	5.70	740	1080 × 470	VNII for Footings and Foundations, 1952-53	"
spring-mounted motor					
1.10-4.45	0.75 2.90	940	500 × 390	VNIIGS, 1951	In use
1.10-4.45	0.75-2.90	1080	520 × 500	VNIIGS, 1953	"
1.90-7.50	1.40-5.55	1375	630 × 530	VNIIGS, 1953	Projected
3.50	2.80	1650	600 × 650	Lengide P, 1952	In use
5.90	4.2	—	—	Lengidroénergoproekt, 1953	"

The rate of penetration in water-saturated sandy soils, according to D. D. Barkan [7], reached values of 5-6 m/min; that is, after 1-2 minutes the drill had penetrated to the entire depth required for the hole (6 m). This rate is ten times the rate of manual percussion-rotation drilling, a saving that clearly indicates the promise of vibrodrilling. However, the effectiveness of geological exploration by drilling is not determined solely by the rate of penetration of the drill.

The chief task of exploratory drilling is to obtain the most precise geologic information on the section drilled through, from samples of the ground, which are collected by raising the drilling device. From this point of view the drilling rig used by Minmashstroi was not without its disadvantages. While admitting the possible preservation of the entire sequence and thickness of the soil layers drilled through and also the possible preservation of the structural and textural features of the soil during a single operation of the drill bit through a depth of 5-6 m, i.e., through the entire length of the drill pipe (a possibility, it may be pertinent to remark, that was not specially investigated), we should note that the hydrogeologic information concerning the sequence passed through by this method of drilling will be incomplete. In making but a single penetration of the drill to the entire planned depth of the hole, the position of the water table is not determined. A measurement of the water level in the hole after extraction of the drill is not always possible, since the walls of the hole are generally destroyed during the extraction process. When several separate water-bearing horizons are present, it is generally impossible to establish the fact, since the isolation of one of the horizons by covering it with casing is impracticable in this procedure.

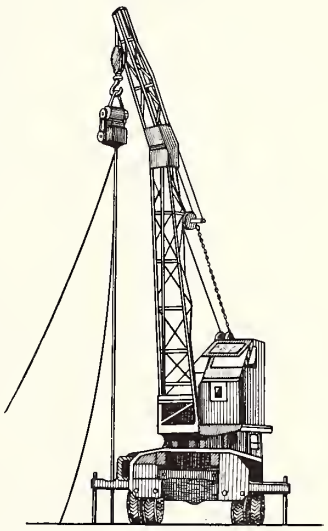


Fig. 26. The Minmashstroi vribrodrilling rig mounted on a "Yanvarets" mobile crane.

It is also impossible to ascertain the hydraulic properties of a water-bearing horizon: the presence or absence of pressure, a quantitative evaluation of the flow of water into the hole, etc. When the drill passes through weak soils that are covered by denser soils, dense soils are inevitably retained in the lower part of the drill pipe, not

dislodged as the drill penetrates the weaker soils. The device is driven into the ground like a pile, and, naturally, cannot give a true picture of the geologic section.

These disadvantages have also been noted by M. G. Efremov [34], who pointed out that, in using a vibrodrilling rig of the indicated type in 1950-51, " . . . in its initially proposed form, considerable disturbance to the structure of the soil, compaction of the soil, distortion of data concerning depth to individual layers of soil, difficult passage through dense soil, and loss of record of any weakly swelling soil from the logs were noted."

Another disadvantage of the indicated vibrodrilling rig is the necessity of using a mobile crane or some other unwieldy mechanism with a high jib not designed for exploratory projects. In addition, vibrodrilling operations with such a rig are limited by the accessibility of the area to be investigated and by the suitability of the region for municipal construction and railway lines.

At the same time it should be noted that the simplicity of construction of the Minmashstroi vibrodrilling rig, the elimination of the necessity of screwing and unscrewing the drill mountings (a most laborious operation), and the simplicity of the technological process of drilling are great advantages of the described drilling rig; the rig may therefore be used successfully in engineering geologic studies at accessible construction areas for large structures requiring the drilling of a great number of shallow holes; it may also be used in exploring deposits of structural sand and clay.

As a corrective for this technique of vibrodrilling, to enable one to determine water content of the soil, it is recommended that subsidiary holes be drilled by manual percussion-rotary methods within the general exploratory grid.

b) *Drilling Equipment Designed by Lengiprorechtrans.* The experiments of D. D. Barkan were repeated in 1951 by P. S. Yatsenko (Lengiprorechtrans); holes were drilled to depths ranging from 5 to 12 m under field conditions [89].

The initial construction of the Lengiprorechtrans vibrodrilling rig included a BT-6 vibrator driven by a 3-hp benzene boat-motor, "Union." An ordinary drilling derrick was used to raise and lower the drill assemblage. The bit was a rod of angular steel 2-2.5 m long, square in cross section and having beveled corners. The end of the rod was sharpened.

Drilling was accomplished by sinking the rod into the ground its full length; after this the rod was raised, the sample collected, the interval of soil examined and described, and the bit cleaned. An extension rod was used to extend the drilling to greater depths. The terminal rod was driven into the new interval, the upper limit of which was marked by the bottom of the preceding interval of penetration. Although the walls of the hole partly caved in after the removal of the bit and the new penetration involved some of the caved soil, it was found possible to distinguish this part of the soil from the new interval. The position of the water table was determined by the wet part of the rod and of the soil, and, when the walls did not cave, by direct measurement with a normal gate valve.

The merits of the first design of the Lengiprorechtrans vibrodrilling rig are found in the possibility of operating under any conditions regardless of the energy source. The rig may be transported in dismantled form by hand or in a hand cart. The benzene boat-motor of 3.5-hp proved to be sufficiently powerful to drill holes to depths of 10-15 m, and it required but a small quantity of fuel.

At the same time, as one of the first drilling rigs designed for use under unfavorable field conditions, this rig naturally has a number of disadvantages: difficulty of controlling the motor, which is placed above the vibrator and which thus occurs at a considerable height above the ground, being reached only by means of a ladder or of a platform built on the drill derrick; during the drilling of the second and subsequent intervals there arises real danger of mixing soils and of distorting the actual geologic section. It is true that the designer proposed a combination of separate elements of the same cross section for increasing the length of the cutting bit to drill at deeper intervals, but this proved to be difficult.

In succeeding operations Lengiprorechtrans, as have other organizations, has rejected the use of special drilling bits, since no advantages of these bits over those with circular (tubular) cross section have been observed; moreover the use of these bits has limited the development and improvement of vibrodrilling techniques.

In recent years Lengiprorechtrans has developed a vibrodrilling rig to be mounted on a truck [90]. An interesting feature of this design is the use of the truck for driving the vibrator by means of a flexible shaft (Fig. 27). This technique eliminated the necessity of mounting a separate motor on the vibrator, lightened the load on the drill assembly, and gained easy control of the system without direct dependence on a source of energy.

An important element of design in the new Lengiprorechtrans vibrodrilling rig is a hole through the vibrator for

passing the column of drill rod. This arrangement permits the vibrator to be fastened at any height, whereas in other designs the vibrator had to be attached to the top of the drill string. The presence of the hole guarantees easy control of the rig at a level within the height of a man. The vibrator with the hole through it need not be removed from the drill rod, but it may be pushed aside with the adapter whenever desired.

This rig employed a BT-6 vibrator and a GAZ-51 motor truck. A disadvantage of this design has been pointed out by M. G. Efremov [34]: a limited choice in power of vibrator, since the limiting power of drives for existing flexible shafts is 3-4 kw. However, for shallow holes this power is perfectly satisfactory.

Lengiprorechtrans also designed and manufactured a light vibrodrilling rig, which may be transported on a litter [60]. This portable rig is operated from a motor by means of a flexible shaft (Fig. 28). The vibrator has a hole through which the drill rod may be passed, and, consequently, the vibrator may be fastened at any height on the drill string in much the same way as a rotating collar is attached to drill rods during hand drilling; this feature greatly facilitates the operation. The raising and lowering of the equipment in this operation are effected by means of an ordinary drilling tripod with a winch or with a light pile-driving hoist.

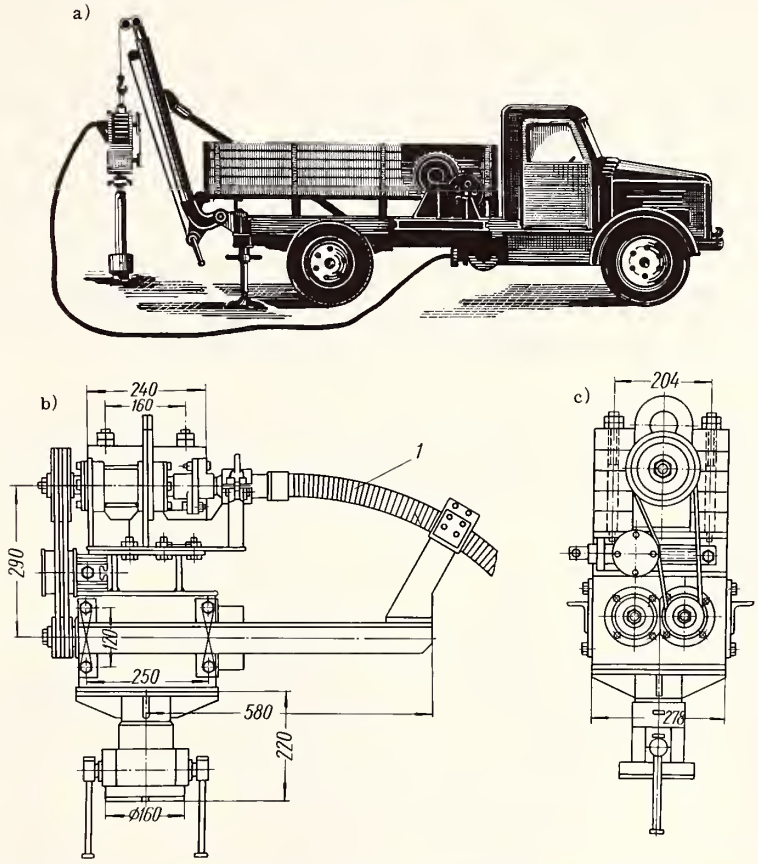


Fig. 27. Vibrodrilling rig mounted on a truck (designed by the engineer G. D. Kozlov, Giprorechtrans): a) transmission of power from engine to vibrator by means of flexible shaft, b) connection of flexible shaft (1) to engine, c) view of the system of shafts in the vibrator.

c) *Vibrodrilling Rig Designed by Lengiprotrans.* Simultaneously with the appearance of the first Lengiprorechtrans vibrodrilling rig, G. M. Babot and N. M. Markova, coworkers at Lengiprotrans, developed a somewhat different design. In this construction sludge pumps for a standard hand percussion-rotary rig, 70 and 95 mm in diameter, were adapted for the drill tips. The shoe and valve were removed from the pump and the edges of the remaining cylinder (the barrel) were sharpened "conically." For easier penetration of the barrel and for convenience in studying the features of the soil taken from the hole in the form of a column (core) from the filled barrel, the barrel had a longitudinal perforation and a solid (unperforated) end 10-15 cm long. The operating length of the barrle is 2.1-2.3 m.

In addition to barrels prepared from sludge pumps, Lengiprotrans used a split core sampler 1 m long for a drill tip. The use of this sampler permitted one to view the entire column (core) of soil taken from the hole and to observe all the structural peculiarities.

The barrel was sunk by means of a rod 42 mm in diameter, which was added to according to the depth of the hole. A single penetration of the apparatus corresponded to the length of the operating segment of the drill tip, and this factor necessitated repeated penetrations and removals of the drilling apparatus.

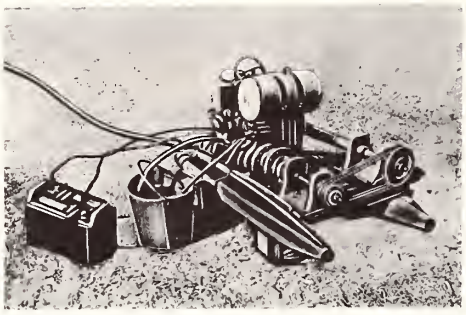


Fig. 28. Portable vibrodrilling rig of the engineer P. S. Yatsenko (motor is on litter).

In order to be assured of stable walls in the holes, ordinary casing was provided for from the standard assembly of 127/115 and 89/78 mm pipe. A vibrator was found especially effective in sinking and extracting the casing, greatly facilitating this laborious and difficult operation. The sinking of casing during vibrodrilling guaranteed reliable determination of the geologic section and of the hydrogeologic conditions.

The penetration of the drill assembly was initially effected by a BT-6 vibrator, which was driven by a 3.5-kw electric motor. However, experience proved that greater stability was attained in the operation by using a shunt alternating-current motor, although such a motor requires greater power at the instant of starting than a direct-current motor. However, as O. A. Savinov [69] and others have noted, the most stable of electric motors will not hold out for more than a few hours of uninterrupted operation.

This disadvantage was removed by Lengiprotrans in later vibrodrilling operations by using a spring-mounted electric motor of the VPM-1 type (designed by O. A. Savinov and A. Ya. Luskin), which was set on a spring-mounted plate that eliminated the vibration. A general view of the VPM-1 vibratory sinker is illustrated in Fig. 29.

The VPM-1 vibratory sinker consists of the following basic components: vibrator, electric motor, a supporting frame from which the motor is suspended, a V-shaped belt drive, spring mounting, and a dismountable head. The vibrator system consists of a housing and two shafts with gears and cams. Each shaft is supported by a double row of radial ball bearings. The housing has holes on the outer side of the base to accommodate bolts for attaching the head.

The kinetic moment of the vibrator ranges up to 60 kg/cm; the frequency is 1500 oscillations per minute. The maximum thrust is 1.5 tons. The power of the electric motor is 3.7 kw. The over-all weight of the sinker is 150 kg, including the weight of the vibrator itself, which is 50 kg.

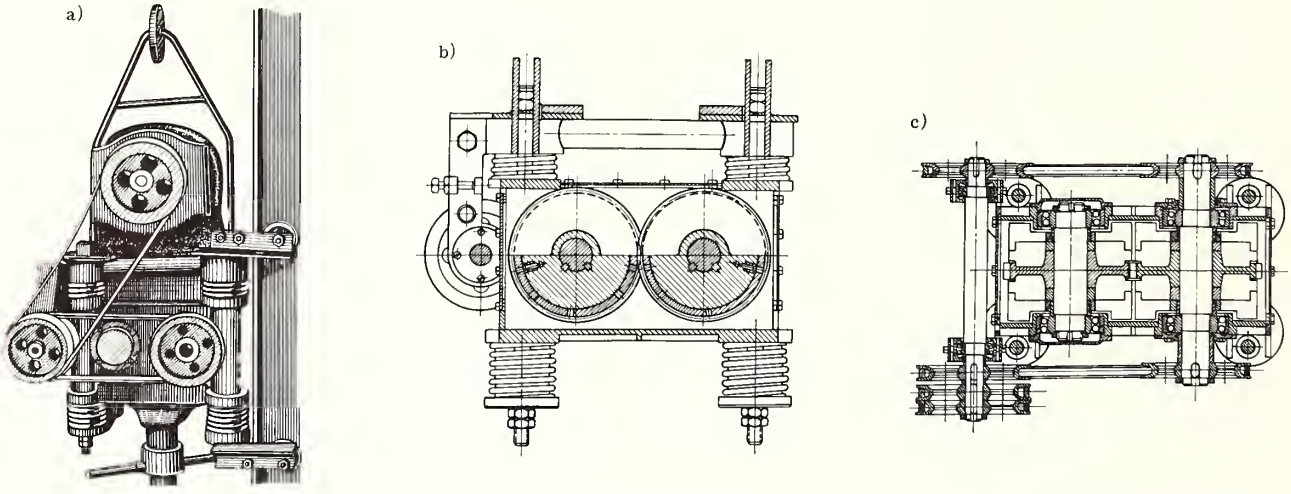


Fig. 29. The VPM-1 vibratory sinker of O. A. Savinov and A. Ya. Luskin: a) general view, b) vertical section, c) horizontal section.

For hoisting, Lengiprotrans uses a sectional tripod of metal pipes 60 mm in diameter, strengthened in the middle by metal braces held on with bolts.

The electric power source is a generator mounted on a truck and driven by a special device from the truck engine. The vibratory assembly and the drilling apparatus are raised and lowered by means of a cable that passes over a pulley of the derrick and is fastened to a rotating shaft (reductor) in the forward part of the truck. A general view of the Lengiprotrans vibrodrilling rig is shown in Fig. 1.

In places where it is difficult to get the truck directly to the drilling site, or when there is an outside source of electrical power (such as when operating in cities), electrical current may be supplied to the motor operating the vibrator by a cable of required length. The drilling apparatus is raised and lowered in such cases by means of an electrical hoist attached to a tripod.

The procedure of vibrodrilling with the Lengiprotrans vibrodrilling rig differs little from that of hand drilling. After the tripod is set up the drill tip is attached to the vibratory sinker by means of a threaded coupling and a lock nut. The drill unit is then placed in a vertical position, the drill tip against the ground, and the vibrator is started. As the drill tip penetrates the ground, the cable passing through the pulley of the derrick and supporting the vibratory sinker gradually unwinds. The drill penetrates the ground to a depth corresponding to the length of the operating part of the bit; then the instrument is raised, samples are taken, and the interval is examined and described. Further operations are carried out by lengthening with drill rod and repeating the procedure of penetration and removal.

Where it is necessary to reinforce the walls of the hole with casing, water-bearing horizons are spanned by pipe of a smaller diameter.

In 1952-53 the Leningrad Institute of Railway Transport Engineering, in cooperation with Lengiprotrans, first conducted special studies for discovering possibilities of using vibrodrilling for geological engineering purposes [25]. The investigations involved the study of accuracy of geologic sections obtained during vibrodrilling, the distortion of laboratory characteristics, and other problems.

On operating a vibrodrilling rig of the indicated design, proper techniques were noted for penetrating several soils difficult to drill. Thus, in water-saturated and slightly consolidated soils (saturated sands and argillaceous sands and supersaturated clays and muds in which the walls slumped immediately on extracting the drill), it was found advisable to sink casing at the same time the hole was being drilled. To accomplish this an ordinary rotating collar was attached to the drill rod, so placed that it rested on a sleeve on the protective tip of the casing pipe as the drill bit penetrated the ground. During this procedure the lower end of the bit should precede the sole of the casing pipe by 0.3-0.5 m. Thus, the casing pipe for reinforcing the walls of the hole is emplaced at the same time the hole is being drilled.

The sinking of holes in unconsolidated soils by driving the pipes first and then drilling out the "sample" cannot be recommended, since this procedure leads to considerable deformation of the soil and to a marked disturbance of the structures and textures. Such a method may be acceptable only for drilling quicksand, in which it is impossible to preserve the structures by any manner of drilling. In this case the casing pipe is driven to the water-supporting horizon, after which the "sample" may be drilled out with no difficulty. If the thickness of quicksand is great, it is advisable to sink the hole with a single penetration to the planned depth, as was done by Minmashstroi.

The vibrodrilling rig designed by Lengiprotrans has completed a great amount of drilling (measured in thousands of running meters). The depth of individual holes has reached 25-26 m. In particular, a great amount of drilling has been done in surveying railroad lines in virgin regions of Kazakhstan in order to investigate structural areas and to explore sandy deposits. The chief of party, A. D. Vinogradov, in doing field work on structural aggregate, improved operation by employing a mast-jib hoist mounted on the body of a truck instead of using a tripod, an arrangement that entails considerable expenditure of time. This adaptation permitted a great acceleration in productive drilling operation.

The design of the Lengiprotrans vibrodrilling rig also has its disadvantages, one of which is the laborious work of auxiliary processes: screwing and unscrewing the rod, connecting and disconnecting vibrator assembly with the drill mounting, etc. However, even with this defect, the use of vibrodrilling in exploratory work gives incomparably more effective results than ordinary manual percussion-rotary drilling.

The vibrodrilling rig designed by Lengiprotrans has been used by the institutes of Glavtransproekt in surveying for railroads, and Sibgiprotrans has drilled successfully with vibratory equipment in permafrost.

d) *Vibrodrilling Rigs Designed by the Leningrad Branch of Gidroénergoproekt.* In the designs of these rigs the vibratory sinker VBL-3 (Fig. 30) has been used, using an internal-combustion engine (the rigs have been designed by A. E. Leingol'd and S. D. Nezdyurov). The kinetic moment of the vibrator is 50-100 kg/cm, the frequency 1500 oscillations per minute, and the weight 240 kg. An internal-combustion motor of the ODV-300 type generating six horsepower is equipped with a friction clutch that is operated from the ground. When electrical power is available, the internal-combustion motor may be easily replaced by an electric motor.

For hoisting, the Lengidroénergoproekt vibrodrilling rig employs not only a drilling tripod of metal pipe but also a special adaptation in the form of a crane jib or mast. To bring the drill column to a vertical position and to avoid maintaining this position by tightening and loosening the cable, some Gidroénergoproekt designs have control

braces welded from channel iron. The vibratory sinker is connected to the control braces by rollers that move between the flanges of the channel bars.

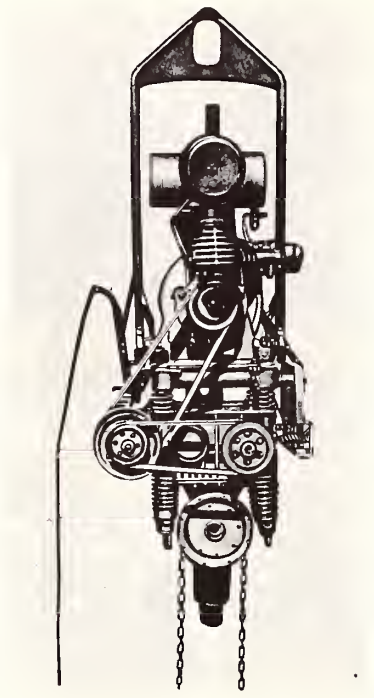


Fig. 30. General view of the VBL-3 vibratory sinker designed by Gidroénergoproekt.

Depending on the type of hoisting arrangement, the control braces are fastened at the upper end to the tripod or they are made part of the special equipment mounted on the truck or tractor. One of the Lengidroénergoproekt designs of vibrodrilling rig mounted on a NATI tractor and equipped with a VBL-3 vibratory sinker is illustrated in Fig. 31.

The drill bit consists of a barrel up to 168 mm in diameter with a slit; the barrel is equipped with a closing device (when needed) in the form of a valve, built into the lower part of the barrel and serving to hold the soil in. With this drill barrel it was found possible to collect highly oversaturated and "quick" soil.

The drilling was performed by successive penetrations to the depth of the functional part of the bit; after each penetration the apparatus was extracted and the perforated interval was examined and described. Standard casing was used to reinforce the walls of the hole in water-bearing soils.

A significant improvement in the Lengidroénergoproekt vibrodrilling rig is the construction of a head that permits the operator to couple the drill assembly to the vibratory assembly on the ground. Ordinarily this coupling is effected when the equipment is being rasied, that is, when the vibratory assembly is suspended, and the task is extremely inconvenient in this position.

The head is jointed (Fig. 32). The revolving part of the head (1) is a bushing with conical internal threading for coupling it with the bit or with the drill rod, and it slips freely on the axle (2), which is attached to the flanges (3) welded to the plate (4). A chain pulley (5) is slipped on the threaded cone of the axle. The connecting part of the head freely rotates on the axle (2), but in a vertical position it rests on the thrust axis (6).

Fig. 31. The Gidroénergoproekt vibrodrilling rig mounted on an NATI tractor.

The drill assembly may be attached on the ground to the jointed head at any position of the vibratory assembly. After the connection is made, the vibratory assembly is raised and the drill assembly with the rotating part of the head is brought to a vertical position. At this time the rotating part rests with its projection on the thrust axis (6). Rigidity of the rotating part is achieved on the ground by rotating the pulley with the chain. On rotation the pulley screws into axle (2) and the rotating part is squeezed tight by the flanges of the head.

A significant improvement in the design of the Lengidroénergoproekt vibrodrilling rig is an arrangement for control from the ground with a friction clutch; this permits one to start the motor at idling speed, without load. It also makes it possible to switch the vibrator on and off without stopping the motor.

The VBL-3 vibratory assembly contains special bits, a "vibrosonde," a vibratory sludge pump, and a sampler, which permit holes to be drilled in loose sand and in clay soils.

In recent years Lengidroénergoproekt has developed and manufactured a group of devices for drilling holes with diameters up to 219 mm to depths reaching 40 m [47]. These devices include a) a self-propelled rig, b) a vibrodrill of the immersible type, and c) a vibrator for sinking and extracting pipe.

The self-propelled rig (Fig. 33) mounted on a DT-54 tractor permits a high rate of drilling in the field. The tractor is equipped with a folding metal mast 8.7 m high and a two-drum friction hoist having a load capacity of two tons. For a power source for the electric motors (for the vibrator and the hoist), an SG-35 generator with a

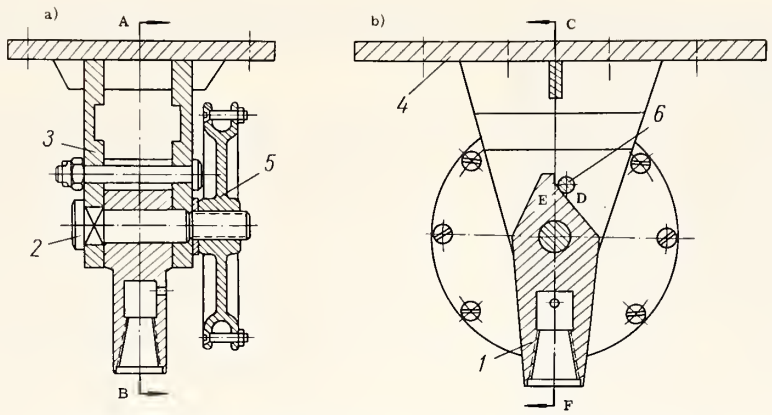


Fig. 32. Head designed by Gidroénergoproekt: a) section through CDEF, b) section through AB.

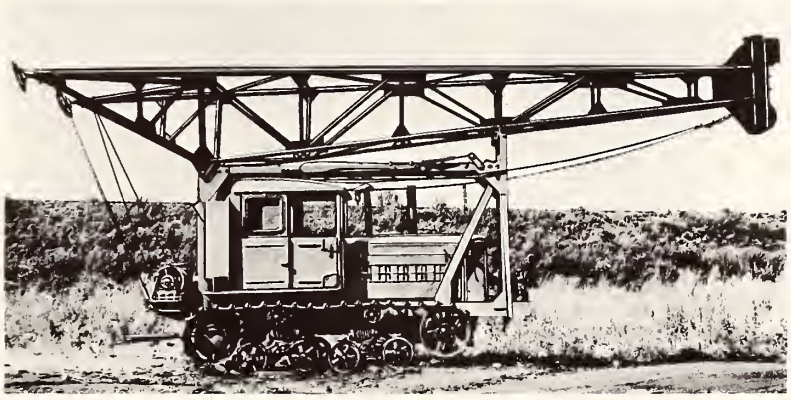


Fig. 33. Self-propelled vibrodrilling rig designed by Lengidroénergoproekt, mounted on a DT-54 tractor.

power output of 28 kw is mounted on the tractor; the generator is driven by a connection with the power take-off box on the tractor.

An immersible vibrator, so far as is known, was first installed by Gidroproekt [22]. However, tests on this installation in 1953 showed the vibrator to be inadequately sealed, and it was impossible to drill below the water table. The defects have been eliminated in the immersible vibrodrill designed by Lengidroproekt.

The Lengidroénergoproekt immersible vibrodrill (Fig. 34) has been designed to drill holes with a diameter of 219 mm (8 in.). It consists of a vibrator, a special electric motor, and a drill bit attached to the vibrator. The vibrator and the electric motor are enclosed in a sealed pipe; the over-all weight is 195 kg.

The vibrodrill is suspended on a cable that passes through a pully attached to the mast of the tractor assembly (Fig. 35). During drilling the vibrodrill is lowered to the bottom of the hole; it penetrates the ground by virtue of the vibration and is then raised by the hoist to the surface for collection of samples and examination and description of the interval; the process is then repeated.

This type of vibrodrill permits one to replace drill rods with cable, and this eliminates the laborious task of screwing and unscrewing rods, facilitates the raising and lowering of the drill assembly, and does not require hoisting equipment for heavy loads. In addition, the penetration capacity of the vibrodrill does not decrease with increasing depth of drilling in the hole, as observed with a string of rods because of transmission of the vibration to the bit through a long column of rods that are insufficiently rigid when connected.

Experimental drilling with the Lengidroénergoproekt immersible vibrodrill gave positive results.

For driving and extracting casing in deep holes the Lengidroénergoproekt has designed and manufactured a powerful vibrator (Fig. 36) driven by two electric motors of 10 kw each. The vibrator has an inner opening through which the pipe is passed. According to S. D. Nezdyurov, one of the designers, this vibrator has been used

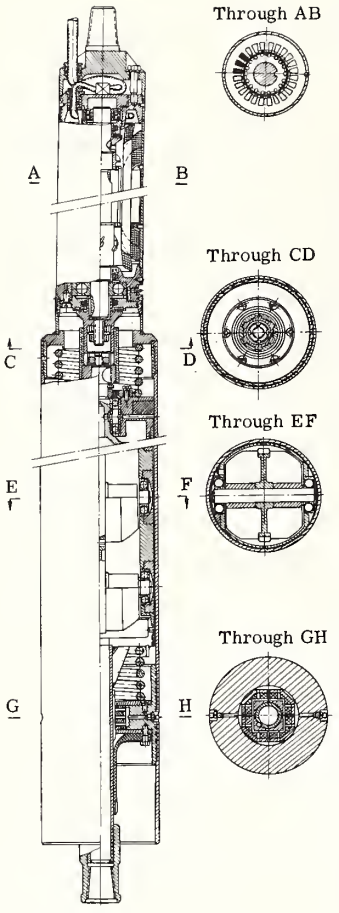


Fig. 34. Diagram of immersible vibrodrill designed by Lengidroénergoproekt, with sectional views at appropriate positions (through AB, CD, EF, and GH).

successfully for extracting a column of pipe 9 in. in diameter and 70 m long that had been in the hole for over a year. Previous attempts to extract this column of pipe had been unsuccessful.

e) *Vibrodrilling Rig Designed by Lenpromstroiproekt.* This rig has been mounted on a very mobile GAZ-63 truck with a VPM-1 vibratory assembly. The VPM-1 vibratory assembly has been improved by the addition of a centrifugal clutch, placed on the shaft of the electric motor and serving to decrease the starting moment. The hoisting equipment consists of a brace placed in the back part of the truck body; this brace is capable of being oriented. The brace is sufficiently high to permit the handling of a drill line up to 2.5 m long. When the truck is being moved the brace is lowered to a horizontal position. For raising the vibratory and drill assemblies a hoist with load capacity of three tons is employed; the hoist is supplied from a power take-off box on the truck. The electrical power for the vibrator is derived from a generator, which is also connected to the power take-off in the truck.

Drilling with this rig is effected by successive additions to the column of pipe. The column of pipe, with diameter from 3 to 6 in. consists of several sections, the length of which corresponds to the height of the directional brace. The sections of pipe are connected by means of sleeves. Longitudinal slits extend along the length of each pipe, except for the ends where the connections are made.

The following operational procedures were noted while drilling by this method: the vibratory assembly was connected at the start to the first section of pipe, and this was driven into the ground its entire length. The vibratory assembly was then disconnected from the first section of pipe, raised by the directional brace, and a second section of pipe was added to the first. The vibratory assembly was then connected to the upper part of the second section and both sections were driven into the ground. In this way sections were added in sufficient numbers to attain a desired depth for the hole.

The column of pipe and the soil filling it were extracted by a hoist, the individual sections being disconnected (unscrewed) as the column was raised. After the pipe had been extracted, samples were collected and the section of soil was examined and described. It should be noted that in sinking holes by this method the loss of core amounted to 0.7 m in a 10-m segment.

This method of drilling is similar in principle to the technique of vibrodrilling with the Minmashstroi rig, but it differs in not requiring a heavy-duty hoisting arrangement involving a crane or some other similar device.

In 1954, Lenpromstroiproekt, together with VNIIGS, conducted special experiments to discover the accuracy of determining geologic sections from vibrodrilling data as compared with the results of hand-drilling methods. According to the authors' observations, their data confirm the results obtained by LIIZhT and Lengiprotrans [68].

f) *Vibrodrilling Rigs of VNII for Footings and Foundations.* A great number of experimental and design studies have been made by VNII for Footings and Foundations (Moscow) in cooperation with Mosgorgeoltrest. For driving the drill assembly a BT-9 vibrator and an improved BT-9 model (reinforced) with double the eccentricity were used. For hoisting and moving equipment, a truck-mounted crane with load capacity of three tons was used. The drill tips were special "sondes," manufactured from pipe ranging in diameter from 74 to 168 mm and having a length of 3 m.

Drilling was done in various construction areas of Moscow in sands and clayey sands, dry and moist (or saturated), and also in morainal loams and clays, including heavy clays (in the Lenin Hills). According to V. S. Moskalev [44], Mosgorgeoltrest drilled 50,000 running meters of holes in 1957.

In addition to BT-9 vibrators, VNII for Footings and Foundations has designed a double vibrator with eccentrics having a moment of 300 kg/cm. The double vibrator has two electric motors and there is an opening along the vertical axis for the drill column to pass through. The raising and lowering operations of the mountings are effected differently from those of the vibrator. The hoisting apparatus is mounted on a truck and has two blocks, one for the mountings and one for the vibrator.

In addition to this VNII for Footings and Foundations has conducted tests on various types of drilling tips (sondes) and has noted several methods of procedure during vibrodrilling. Furthermore, it has instituted

experimental work for comparing laboratory characteristics of samples taken from vibrodrilled holes and from hand-dug holes, such as was done by LIIZhT [25]. The results obtained confirm those obtained by LIIZhT.

Besides the work of Mosgorgeoltrest, extensive work has been done by Mosgeolgeodeztrest, GIDÉP, the Hydrogeological Trust, and by other Moscow organizations. These tests were made chiefly with the drilling rig of VNII for Footings and Foundations.

g) *Vibrodrilling Rig of NIGI of the Ministry of the Metallurgical Industry*. This rig was designed and manufactured by the Scientific-Research Mining Institute of the Ministry of the Metallurgical Industry and it passed appropriate tests both in the laboratory and under actual working conditions. The rig uses the principles of vibratory-rotary drilling. It is designed to drill holes to depths reaching 25 m in hard and very hard rocks.

In contrast to other methods of vibrodrilling, the vibrator of this construction is fastened securely to the drill rods, oscillating with them. The drill tip is of special design. The drilling is effected with drilling fluids, as in ordinary core drilling.

According to V. V. Sermyagin [74], this rig has been used to drill in limestones, dolomites, and marls of very considerable strength, using a cutting bit 125 mm in diameter, to a depth of 20 m at a rate of 8-10 m/hr.

h) *Vibrodrilling Rig of Ukruzryvprom*. The original vibrodrilling rig designed by a group of workers at Ukrvzryvprom [19] was intended for drilling shallow and deeper holes in soft rocks. The vibrator is a metallic box 350 × 320 × 220 mm. The box contains two shafts supported on two weights not in equilibrium. The shafts and the weights are so arranged that the drill rod may pass through the box.

The vibrator is activated by an electric motor, which, in contrast to all the other designs, is set apart from the vibrator and transmits motion to the vibrator by means of a belt. A special holding device on the vibrator box is made to house a feeding mechanism; by means of detents the drill rod is clasped at the proper moment. The entire apparatus is mounted on a hand cart; the total weight is 80 kg (Fig. 37).

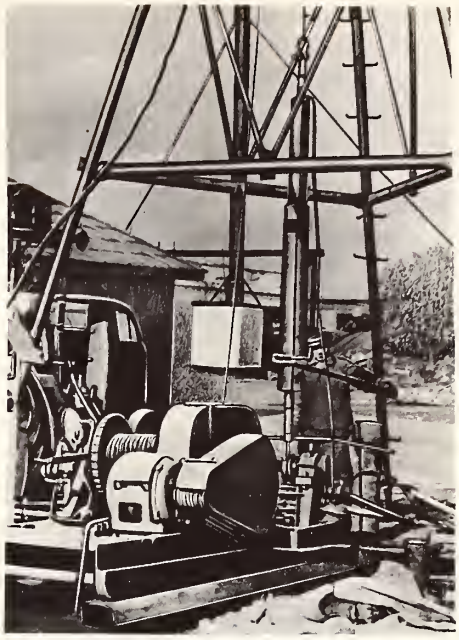


Fig. 35. Vibrodrilling rig designed by Lengidroénergoproekt, with immersible vibrator.

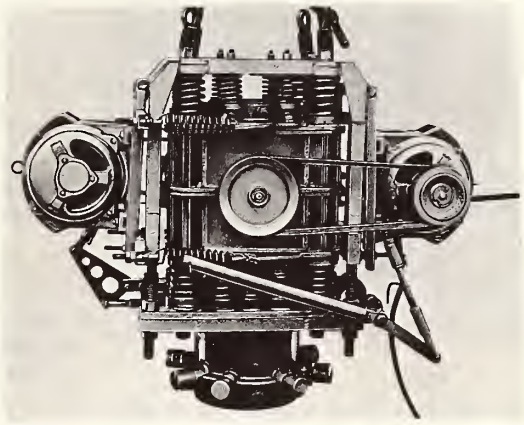


Fig. 36. Vibrator designed by Lengidroénergoproekt for driving and extracting pipe.

The drilling instrument consists of sections of hollow pipe 30 mm in diameter; the tip is conical. The string is added to as the instrument penetrates deeper. One of the designers, A. A. Matveenko [19], has reported that the rig has drilled through dry sand at the rate of 80 m/hr and through dense clay at the rate of 20 m/hr.

The feature that is fundamentally different in the Ukrvzryvprom is the application of a feeding mechanism by means of which pressure is exerted on the drill column. Because of this factor, the vibrator and the motor do not move during drilling; only the drill column with the bit or drilling tip move. Although this apparatus was designed for drilling small shallow holes, with little alteration it may also be used for drilling larger and deeper holes for geological exploration.

i) *Vibrodrilling Apparatus Employing a Hammer Drill*. As reported by the designer at VNII for Footings and Foundations, M. G. Efremov [33], a light hammer drill was developed in 1954 to lessen the weight of the drilling apparatus and to decrease the power of the motor, while preserving, even increasing, the penetrating capacity of the instrument; the improved hammer drill, VMG-2, has been shown by actual tests to give better results than the heavy, powerful BT-9 vibrator.

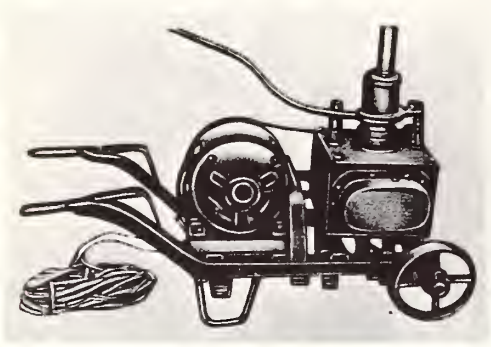


Fig. 37. Vibrodrilling apparatus of Ukrvzryvprom.

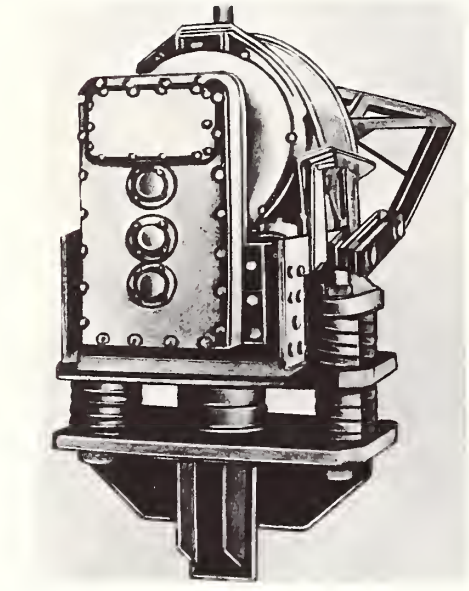


Fig. 38. General view of hammer drill designed by VNII for Footings and Foundations (M. G. Efremov).

The VMG-2 hammer drill weighs 175 kg and is operated by an electric motor with a power of 2.8 kw and a speed of 1450 rpm. The moment of the eccentrics, 50 kg/cm, generates a thrust of 1150 kg; the weight of the striking mass is 108 kg. A general view of this hammer drill is shown in Fig. 38.

The penetrating capacity of this hammer drill was tested at the same time the same property was being tested on the BT-9 vibrator (reinforced), which has a moment of the eccentrics of 200 kg/cm, an oscillation frequency of 1250 cmp, and a generated thrust of 3460 kg. A truck-mounted crane with a load capacity of three tons was used for hoisting and transporting both rigs.

For a drilling tip, sondes were used, prepared from pipe 145, 100, and 73 mm in diameter. The soil in the areas where the tests were made consists of morainal clays and loams, semi-indurated and becoming plastic only with difficulty, and containing stones up to 135 mm across.

The tests demonstrated that the hammer drill possesses better penetrating capacity than the BT-9 vibrator (reinforced), especially in clay soils; in such soils the rate of penetration of the hammer-drill device proved to be four times the rate of equipment with the BT-9 vibrator. In this test it was noted that the decrease in penetrating rate with depth of the hole, normally observed with vibrators, was less when the hammer drill was used.

The VMG-2 hammer drill requires about one-third the electrical energy the vibrator employs. In the comparative tests the greatest demand of the hammer was 3.5 kw, of the BT-9 vibrator 10.5 kw. The average power demand was 2 kw for the hammer drill and 5.5 kw for the vibrator.

In recent years Mosgorgeoltrest has used hammer drills chiefly of the VMG-5 type, weighing 110 kg and driven by a 1.7-kw electric motor. According to V. S. Moskalev [44], this hammer drill performs more work and secures better exploration data than other types.

The advantage of the hammer drill over the vibrator, as noted above, shows that it is possible to produce a lighter vibratory drilling apparatus by replacing the ordinary vibrator with a vibratory hammer. According to M. G. Efremov [34a], the use of hammer drills guarantees rather good preservation of soil samples and permits a full representation of the geologic content of the sequence drilled through.

In reports of the Fourth International Petroleum Congress [5a], it has been recorded that vibrodrilling has been employed in sinking deep oil wells. According to these reports the drilling rate in granite is 9 m/hr.

All the material discussed above indicates that vibrodrilling now occupies a firm place among methods of geologic exploration. At the same time it should be noted that wider use of the method is limited by the lack of improved designs of vibrodrilling rigs and the lack of factories for manufacturing and distributing such rigs. Until now, each organization doing vibrodrilling has designed and manufactured its own equipment. These organizations have not carried on any great volume of experimental work. This abnormal situation must be eliminated as quickly as possible.

The data we have discussed concerning certain known and tested vibrodrilling rigs show that two techniques of vibrodrilling have been contemplated in introducing this type of geological exploration. The first involves a single penetration of the drill tip in the form of a solitary pipe with a slit or with a subsequently attached column of pipe, the single penetration extending to the entire planned depth of the hole (Minmashstroi, Lenpromstroiproekt). The second method provides for repeated penetration of a drill tip 2-2.5 m long with subsequent or simultaneous sinking of casing (Lengiprotrans, Gidroénergoproekt).

The first technique undoubtedly has great advantages in the amount of work it can accomplish, but it requires a tall hoisting system (for a drill tip consisting of a single pipe or of a sonde), and, in addition, it makes it difficult to make hydrogeologic observations, since it is impossible to make direct measurements of the water level in the hole. However, it should be kept in mind that the water level in the hole may be determined by a study of the section of soil drilled through, i.e., by the lithology, the moisture content, and the structure and texture of the soil (which are well preserved in the column of soil extracted). This indirect determination of the saturated zone in the soil is possible only for unconfined water. It is practically impossible to determine the position of the water level in the confined zone of an aquifer, especially when the level is shallow. It is clearly most effective to combine both methods of vibrodrilling in a single rig, in order that individual holes at a particular site may be drilled by the other method, such as exploratory holes for detailed information, drilled by repeated penetration of the drill tip and accompanied by the sinking of casing and the necessary observations of hydrogeologic features.

The general disadvantage of the vibrodrilling rigs discussed above is that they are cumbersome (heavy and requiring hoisting equipment); because of this the rigs are difficult to transport, especially were roads are lacking; and this is the normal situation when exploring uninhabited regions. In addition, especially when drilling by repeated penetrations of the drilling tip, the auxiliary operations require a great amount of time.

In order to facilitate the raising and lowering of the drilling apparatus and to make it easier to transport, the Leningrad Mining Institute has produced a vibrodrilling device that weighs 75 kg; it has been successfully used in drilling shallow holes (about 5 m). Lengiprotrans is at the present time employed in attempting to use a vibrodrilling device that weighs 30 kg for sinking shallow holes; it is proposed that the drilling be done without a derrick.

Attempts have also been made to produce a light electromagnetic vibrodrilling device (N. Ya. Drobyshevskii at Lengidroproekt, 1954), but these efforts have not yet proved successful.

On the basis of the existing designs of vibrodrilling equipment discussed above (they should now be considered as first attempts, showing us the courses that have been pursued in this field), we may note the basic features of a vibrodrilling rig, the design of which should incorporate the most successful aspects already discovered. Such a rig should include the following features:

1) an opening through the vibrator permitting the vibrator to be attached to the drilling assembly at any height;

2) an arrangement for moving the vibrator aside, away from the hole;

3) a feeding mechanism (a clamping lever) for transmitting pressure to the drill assembly without raising the vibrator (such as the vibrodrilling arrangement of Ukrvzryvprom);

4) a directional arrangement for producing a vertical hole.

Vibrators used in drilling the very numerous shallow holes during engineering geological investigations should be light in weight and should have a high frequency and small amplitude. It is also possible to use small hammer drills, considering their successful application by Mosgorgeoltrest, when soil samples need to be preserved.

In order to eliminate the laborious task of screwing on and unscrewing the drill rods, the following method may be employed. After the first penetration of the drill bit, casing is driven simultaneously with the drilling, the bit preceding the foot of the casing by 0.3-0.5 m. The vibrator attached to the pipe effects the sinking, and the drill tip, suspended on a flexible cable, is clasped in a special device in the lower part of the pipe and is carried along with the pipe (Fig. 39). When the cable grows taut, the indicated device frees the drill tip, and the drilling assembly may be freely raised on the cable. After logging, collecting samples, and cleaning the drill tip, the bit is again lowered into the hole, fastened to the lower part of the pipe (or the column of pipe), and drilling is continued. This technique eliminates the necessity of screwing and unscrewing rod, and thus greatly increases the amount of work that may be done. Furthermore, this method does not require a tall hoisting device, since only short intervals (2-3 m) are drilled; in this way core recovery is good and hydrogeologic observations are conveniently made.

Successful vibrodrilling depends in great measure on the shape and design of the drill tip. As has already been noted above, the first attempts at vibrodrilling (Minmashstroi, Lengiprorechtrans) were made with tips in the form of an acicular rods of angular steel, having a square cross section with beveled corners. Later, however, it was found more suitable to use a tip with a circular cross section (a vibratory barrel, vibrating sonde, vibrating pump), easily prepared from pipe. The first of these attempts with the modified tips established the fundamental influence of a slit or perforation and the effect of the width of this slit on the penetration rate and on the recovery of the core. For example, it was ascertained that a barrel with a wide slit penetrated more rapidly than a barrel with a narrow slit or with no slit. At the same time, sandy soil spilled out of barrels with wide slits. It was thus found necessary to vary the width of the slit. In clay soils, according to D. D. Barkan, the proper width of the slit corresponds to an arc of 160°; in sands the arc is 120°.

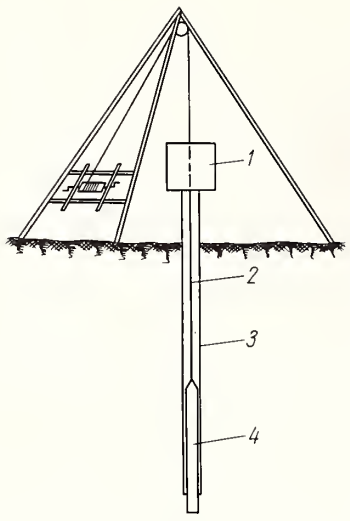


Fig. 39. Vibrodrilling by sinking casing at the same time as the drill tip, which is suspended from a flexible cable. 1) Vibrator, 2) cable, 3) casing, 4) drill tip.

In the experiments by Lengiprotrans and LIIZhT, barrels with a diameter of 115 mm and a slit 4-5 cm wide were used; these barrels were employed successfully in drilling sandy clay deposits of various consistencies.

In a paper of P. F. Palyanov [54], data are cited on the penetration rate of barrels with several slits (channels). According to these data, the best results are obtained by barrels with three slits. For example, in a particular kind of soil (viscous, half-dried clays) a barrel with no slits penetrated a total of 15-20 cm; no further penetration could be effected by operation of the vibrator. When the barrel was extracted from the ground, the soil column (core) showed marked differences in density with height. The upper part of the core was rather soft, whereas the lower part was very strongly compacted.

A barrel with a single slit penetrated 30-35 cm when activated by a vibrator. As in the preceding example, compaction of the core in the lower part was observed, chiefly on the side opposite the slit. In the upper part of the barrel and near the slit no compaction was observed.

A barrel with two slits, placed opposite each other, penetrated 70 cm. The barrel with three slits easily went down 120-170 cm, i.e., almost the entire length of the operating segment, in 1.5-3 min. The width of the slits in all examples was 0.4-0.6 the diameter of the barrel.

A disadvantage of barrels with several slits is their lack of strength. To insure the proper strength, P. F. Pal'yanov [54] has recommended that cross pieces be left, i.e., that the slits be discontinuous, that certain segments of the pipe remain unslitted.

Dimensions of tips prepared from core-drilling pipe are shown in Table 13 (after P. F. Pal'yanov).

The significance of the shape of drilling tips has also been analyzed by VNII of Footings and Foundations [34]. The tips of channel iron and angular iron used by this organization in the initial stages of vibrodrilling did not meet requirements. Experimental work has shown that the best tips are made from thin-walled pipe 100-150 mm in diameter, in no case less than 60-70 mm. The recommended thickness of walls in the tip of the pipe, in order to decrease any resistance, is no greater than 3-5 mm.

Table 13

Dimensions of Drilling Tips

Outside and inside diameters, mm	Thickness of walls, mm		Length of channel (slit), mm	Width of channel (slit), mm
	Pipe	Crosspiece		
146/137	4.5	1.5	2000	60-90
127/118	4.5	1.5	2000	50-75
108/99.5	4.25	1.5	2000	45-65
89/81	4.00	1.25	1500	55-55
73/65.5	3.75	1.25	1500	30-45

Experiments of VNII for Footings and Foundations have shown the desirability also of reducing the inside diameter of the lower part of the tip 3-5%, especially for drilling in clay soils. In this way the effect of the thickness of the walls of the penetrating tip on the core within the pipe decreases sharply, and this insures good preservation of the structural and textural features of the soil.

Both P. F. Pal'yanov and the representatives of VNII for Footings and Foundations recommend a tip with bilateral longitudinal slits for drilling in dense clayey soils.

§ 17. SOME DATA ON THE RATE OF SINKING HOLES BY VIBRODRILLING

The first data on the penetration rate on holes drilled by means of vibrators were published in a paper by D. D. Barkan and others [8] in 1951. In this paper it was pointed out that 150 holes were drilled to depths reaching 6.5 m in seven days; thus, including the time spent in shifting and securing the mobile crane, in collecting samples, and in other auxiliary operations, the productive capacity of a single vibrator amounted to 4.3 holes per hour on the average, i.e., approximately 30-35 times the productive capacity of other devices used for drilling such holes. The actual cost per running foot of vibrodrilled hole amounted to one ruble 20 kopeks, one-twentieth the cost of percussion drilling.

It should be noted that the data cited in some measure actually exaggerate the productive capacity of vibrodrilling; obviously they do not take into account accompanying operations. In particular, the cost per running meter of drilling, one ruble and 20 kopeks according to D. D. Barkan, was obviously computed without consideration of the cost of amortizing the mobile crane or the payment for technical help, logging and related operations, and supervisory personnel. In another paper [7] D. D. Barkan has cited somewhat different data concerning the productive capacity of the same vibrodrilling equipment. He has noted that this productive capacity is but 15-20 times that for hand drilling. But in neither of the indicated papers are there any concrete data indicating the source of the figures presented concerning the productive capacity of vibrodrilling or stipulating what factors were included in computing the cost. It is therefore impossible to judge properly the productive capacity of the vibrodrilling rig or of the cost of operation from the cited figures.

More definite data on the efficiency of vibrodrilling, as compared with manual percussion-rotary drilling, have been obtained by Lengiprotrans during special experimental investigations, in which the Leningrad Institute of Railroad Engineers also participated.

Figure 40 is a graph showing data on drilling rate and casing of holes drilled by vibrodrills and by hand in saturated sandy loams with layers of peat and in plastic loams of average density. The diameters of both types of holes are 127/115 mm. The vibrodrilled hole was drilled to a depth of 16.50 m in 1 hr 11 min; it took 7 hr 49 min to sink the hand-drilled well to the same depth. It required 1 hr 55 min to sink casing in the first hole, 6 hr 43 min in the second. Thus, the rate of vibrodrilling itself was 6.5 times that for manual drilling, and the rate of sinking casing was 3.5 times the manual method. It should be borne in mind that the work was done by an inexperienced crew, drilling in this manner for the first time.

Figure 41 presents a series of graphs to show curves for drilling rates in dense, predominantly dry sands; the processes of actual drilling and of subsidiary operations are distinguished. The horizontal segments of the graphs correspond to time spent on auxiliary operations; the sloping segments represent actual drilling time. It is clear from these graphs that actual drilling, which we understand to mean the penetration of the drill bit into the soil, required very little time as compared with the subsidiary operations, and the proportion decreased noticeably with depth. Thus, in the interval from 0 to 7.6 m, the time spent on actual drilling was 17.8% of the total, on subsidiary operations 82.2%; in the interval from 20.25 to 26.65 m, actual drilling time was but 8.9%of the total, subsidiary operations 91.1%.

The same figure shows a graph for manual drilling in the depth interval of 7.6 to 10.85 m. In this example actual drilling time was 40.7%of the total, subsidiary operations 59.3%.

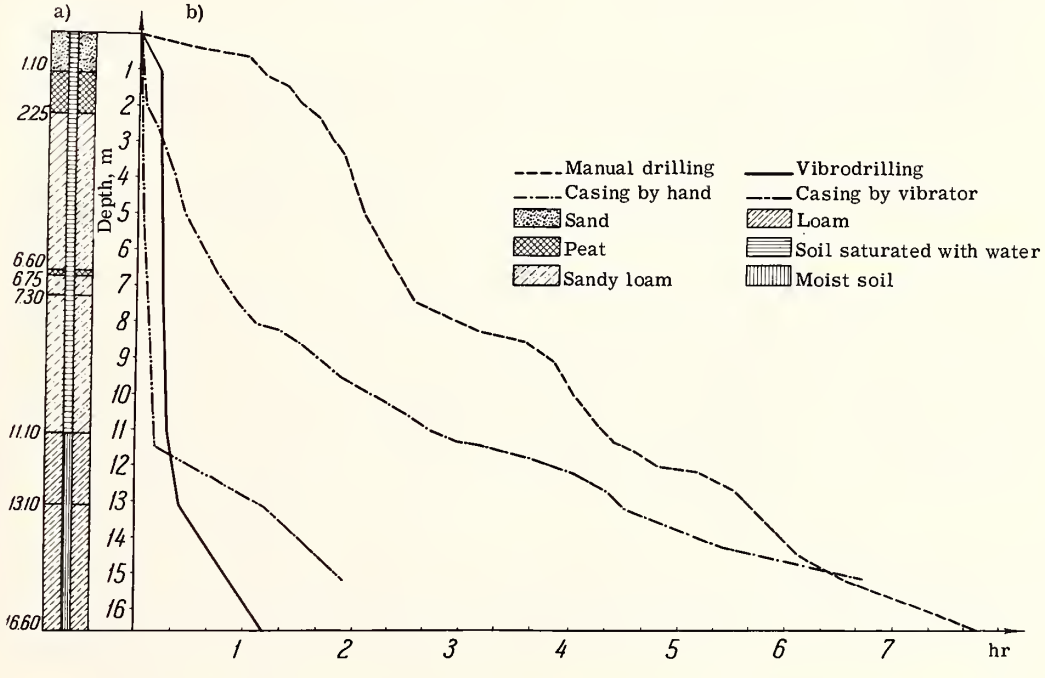


Fig. 40. Comparison of rates of manual drilling and vibrodrilling. a) Lithology, b) curves of drilling rates.

It is clear from the graphs that during vibrodrilling a great part of the time is spent on subsidiary operations. Actual drilling occupies a very negligible percentage of the total time spent in vibrodrilling. From this it follows that improvements in vibrodrilling equipment should be directed mainly to acceleration and alleviation of the subsidiary operations.

O. A. Savinov and other investigators [69] have reported data on penetration rate with the vibrodrilling rig of Promstroiproekt for holes in sand, banded clay, and morainal loam (Table 15).

Table 15

Time Required for Vibrodrilling Holes by Different Methods (after O. A. Savinov and others)

Type of drilling	Depth of hole, m	Average time of penetration of the bit, min	Average penetration rate, m/min
With a 2-in. bit and 4-in. casing .	10	3-4	2.7
With a column of pipe 3 inches in diameter	10	6-7	1.5

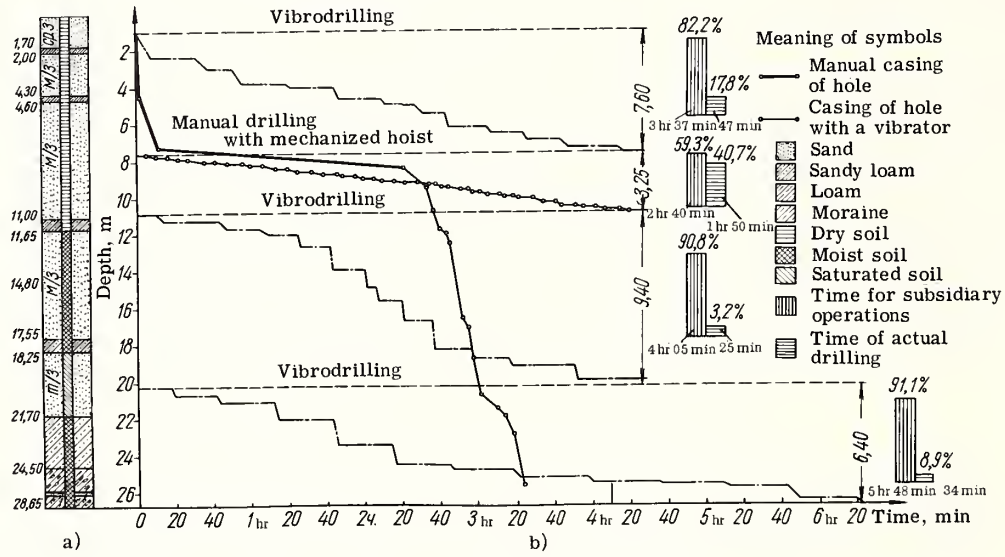


Fig. 41. Comparative graphs for rates of manual drilling and vibrodrilling, subsidiary operations differentiated. a) Lithology, b) curves for rates of drilling and sinking of casing.

Table 16

Comparative Data on Drilling by Hand (with a Percussion-Rotary Rig) and with a Vibrodrill

Type and conditions of drilling	Number of holes in one shift	Number of running meters in one shift	Time required for one hole	Time expended per running meter		
				Drilling plus all subsidiary operations	Drilling operations proper	Actual drilling (penetration)
Manual rig	2	6	3 hr 50 min	1 hr 17 min	0 hr 58 min	0 hr 20 min
Vibrodrilling from a boat with no preliminary setting up of the hole site	4	12	1 hr 40 min	0 hr 33 min	0 hr 07 min	0 hr 01 min
Vibrodrilling from a motor boat after preliminary setting up of the drill site	8	24	0 hr 50 min	0 hr 17 min	0 hr 07 min	0 hr 01 min

A. K. Tokarev [76] has cited data (Table 16) for manual drilling and vibrodrilling with the use of a buoyent medium, under identical geological conditions (the work was done by the Lengiprovodtrans). It may be seen from Table 16 that the rate of vibrodrilling is 4.5 times that of manual drilling, and the rate of actual drilling is 20 times that of manual drilling.

It is interesting to compare the productive capacity and cost of drilling done with the vibrodrill and with the power-driven mechanized AVB-3-100 and UKP-2-100 drilling rigs. The data in Table 17 from Lengiprovodkhoz also show the superiority of vibrodrilling, even in comparison with the power-driven drilling rigs widely used in geological engineering investigations.

Table 17

Comparative Data on the Sinking of Holes by a Vibrator and by the AVB-3-100 and UKP-2-100 Power-Driven Rigs

Index	Manual percussion-rotary rig	Power-driven rigs		Vibrodrilling (with no mechanized hoisting or transporting equipment)
		AVB-3-100	UKP-2-100	
Rate of drilling, meters per shift	4.5	9.0	9.0	12.0
Cost per running meter, in rubles	14.0	5.5	5.5	4.0

As noted above, the principal disadvantage of vibrodrilling is the laborious work involved in secondary operations, as compared with actual drilling. A. K. Tokarev has presented some interesting facts in this connection, having to do with special time measurements on individual operations during use of the Gidroénergoproekt vibrodrilling rig VBL-3. Raising and lowering operations were effected by a manual hoist having a load capacity of one ton; the hoist was attached to a dismountable wooden tripod. The vibrator was activated by an internal combusion engine of the style ODV-300 (single cylinder, two cycle, air cooled), rated at 5.5 hp.

The following operational factors in vibrodrilling were distinguished by A. K. Tokarev:

1) preliminary operations, including unloading of material with movement of material up to 10 m, preparation of an area for the drilling rig, erection of the derrick, mounting the drilling assembly, and adjusting and attaching the bit;

2) drilling proper, including penetration of the bit (actual drilling), unscrewing and attaching drill rod, lowering and raising the drilling assembly, cleaning the hole, cleaning the bit, collecting samples, and sinking casing (when necessary);

3) cleaning-up operations, including extraction of casing, dismantling rig and derrick, and loading of equipment on a truck (with transfer of material up to 10 m).

The relations of these factors to each other may be clearly seen in Table 18.

In analyzing the data in Table 18 one's attention is drawn to the great expenditure of time in preliminary operations, amounting to 21-34% of the total time of the vibrodrilling operation. Under similar conditions, for a hole drilled by manual percussion-rotary methods, the time spent on preliminary work did not exceed 5% of the total. However, in vibrodrilling the drilling proper utilizes 52-66% of the total time, whereas in manual drilling the time spent on this part of the operation amounted to 85-91%.

This analysis also shows that improvements in the design of vibrodrilling rigs should be directed toward easing and curtailing the secondary operations.

Thus, it may be stated that during the period of instituting vibrodrilling operations, to which period the above-cited data refer, even with the imperfections in design, the productive capacity of vibrodrilling is at least 4-5 times that of drilling by manual percussion-rotary methods. There is every reason to believe that when this method is fully established the productive capacity will increase yet more.)

* In this connection it is of interest to note the paper of Ya. I. Sherdyukov and D. S. Pliner: "An experiment in drilling holes by the vibratory method in geological engineering investigations," Zhur. "Osnovaniya, Fundamenty i Mekhanika gruntov" 2 (1959).

Table 18

Expenditure of Time on Individual Tasks during Vibrodrilling (after A. K. Tokarev)

Name of operation	Time spent on individual operations					
	Drill hole No 99		Drill hole No 100		Drill hole No 82A	
	min	%	min	%	min	%
Preliminary operations	50	34.3	48	28.4	60	21.0
Drilling proper	76	52.0	99	58.6	190	66.7
Including:						
a) actual drilling	34	23.3	32	19.0	51	17.9
b) raising and lowering	22	14.6	19	11.3	49	17.2
c) collection of samples and cleaning of bit	20	13.7	16	9.5	15	5.3
d) sinking of casing	—	—	—	—	45	15.8
e) starting and regulating motor	—	—	9	5.3	30	10.5
f) breaking boulders by hand	—	—	23	13.6	—	—
Cleaning-up operations	20	13.7	22	13.0	35	12.3
Totals	146	100	169	100	285	100

§ 18. THE PATTERN OF VIBRATION AND ITS SIGNIFICANCE IN VIBRODRILLING

The principal factor controlling the rate of penetration during vibrodrilling, other conditions being equal, is the intensity of the vibration, determined by the frequency and the amplitude of the oscillations. The approximate value of the amplitude is determined, according to D. D. Barkan, by the following equation:

$$A = K/Q,$$

where A is the amplitude of the oscillations, K is the kinetic moment of the vibrator eccentrics, and Q is the weight of the downward-moving system (in this case the weight of the drill tip, the rod assembly, and the vibrator itself).

Consequently, the amplitude of oscillation during the vibration, which produces more rapid penetration when it is increased, is directly proportional to the kinetic moment of the eccentrics and inversely proportional to the weight of the downward-sinking system that participates in the vibration.

When spring-mounted motors are used, the weight of the motor does not participate in the vibration, and this weight is consequently excluded from the total weight of the penetrating (vibrating) system. This is one of the important advantages of this type of vibrator, since, because of this, the amplitude of oscillation, other conditions being equal (i.e., with the same weight of the drilling assembly together with the vibrator and motor), is increased, and this increases the penetration rate of the system.

From the equation cited above it may be seen that the greatest amplitude occurs during the drilling of the first interval. The deeper the hole the more drill rod there must be, and the weight of the penetrating system is thus increased and the amplitude of oscillation correspondingly decreased, diminishing the penetration rate. The depth of a hole drilled by a vibratory rig, for a definite power of vibrator, is thus limited. This statement does not apply to immersible vibratory systems.

Experimental work by Lengiprotrans and LIIZhT has shown that, when the VPM-1 vibrator activated by a 4.5-kw electric motor is used, holes 20-25 m deep may be drilled. The greatest depth attained in a hole drilled with this vibrator in dense dry sand (Toksovo region near Leningrad) is 26.5 m.

As noted above, the amplitude of oscillation during vibrodrilling varies. This is due, on the one hand, to the increased weight of the penetrating system as the hole becomes deeper and, on the other, to a change in the number of revolutions of the vibrator.

Direct determination of the amplitude of oscillation during the experimental vibrodrilling was not made because of lack of necessary equipment. The computed value at the beginning of an interval amounted approximately to 1-2 mm. As experiments have shown, such a value insures rather rapid penetration when drilling in dry alluvial loams and sands, in dense morainal loams, and in banded clays. It was found possible also to drill to shallow depth in dense bedrock clays (Devonian rocks in the Novgorod region), in marls, and in gravels.

O. A. Savinov and other authors [69] indicate the amplitude necessary for effective penetration of piles into saturated sandy soil and plastic clay soil (Table 19).

During vibrodrilling the drilling assembly may penetrate successfully at lower amplitudes than required for sinking piles. However, the general relationship between amplitude and frequency clearly remains unchanged. Therefore, for successful penetration of the drilling assembly at low frequencies a large amplitude is necessary. At the same time it should be noted that with increase in amplitude there occurs a noticeable increase in deformation of the soil that enters the drill barrel. For this reason, vibrodrilling should be done with high-frequency vibrators, which will insure successful penetration at low amplitudes.

The amplitude, being variable, changes in dependence on the weight of the penetrating system. In this connection it is desirable to design a vibrator that will permit the kinetic moment to be changed, in order to maintain the proper amplitude. At the instant drilling begins the kinetic moment should be at a minimum, since at this time the large amplitude leads to the greatest deformation of the soil and the core cannot be completely recovered. As the drill penetrates deeper the kinetic moment should be gradually increased.

§ 19. SUMMARY

1. At the present time there are several designs of vibrodrilling equipment, more or less successfully applicable to geologic-exploratory drilling. These designs have successfully solved individual details and have accounted for proper relations between the individual components, but there is, as yet, no rig that completely satisfies all requirements.

2. The principal disadvantages of the existing designs are their cumbersome qualities and the necessity of expending a great amount of time on subsidiary operations. Further improvements in the design of such devices should be directed primarily toward the elimination of these disadvantages.

3. The most promising advancement is the widespread introduction of immersible vibrodrills in actual practice and the further improvement in the designs of these devices (decrease in dimensions and weight, and greater stability under working conditions). There is also promise in using vibrodrilling rigs with a feeding mechanism and a stationary vibrator of the type used in the Ukrvzryvprom apparatus; it is also possible to use rotary motion with this arrangement.

4. Despite the imperfections of the existing vibrodrilling rigs, the penetration rate by this method is considerably greater than by hand and by several other types of mechanical drilling. This fact has led to the use of vibrodrilling in a number of the most progressive methods of geologic exploration.

5. The applicability of vibrodrilling, and also the limiting depth of vibrodrilled holes, apart from the geologic conditions, depends on the strength of the vibrator and the design of the drilling apparatus. The apparatus most useful at the present time, relative to a light vibrator (100-150 kg) and drill-rod assembly, permits holes to be drilled in friable rocks to a depth of 25 m. With further improvements in the design of vibrodrilling equipment, the range of application may be considerably extended, both in regard to the rock drilled through and in regard to the depth of hole possible.

Abbreviations of Organizations and Institutes Encountered in Chapter III

GIDEP--State Trust for the Planning of Hydroelectric Power Plants and Developments

Gidroproekt--see Lengidroénergoproekt

Gidroénergoproekt--see Lengidroénergoproekt

Giprosel'élektro--All-Union State Institute for the Design and Planning of Rural Electrification

Glavtransproekt--Main Administration for the Study and Planning of Railroad Transportation

Lengidép--Leningrad State Trust for Planning of Hydroelectric Power Plants and Developments

Lengidroénergoproekt--Leningrad All-Union Trust for the Design and Planning of Hydroelectric Power Plants and Developments

Lengidroproekt--see Lengidroénergoproekt

Lengiprotrans--Leningrad State Institute for the Planning of Transportation

Lengiprovodkhoz--Leningrad State Institute for the Design and Planning of Water Resources and Melioration Development

Lengiprovodtrans--Leningrad State Institute for the Design and Planning of Water Transport

Lenpromstroiproekt--Leningrad State Institute for Design and Planning in the Construction Industry

LIIZhT--Leningrad Institute of Railroad Engineers

Minmashstroi--Ministry of Machine Construction

Mosgeolgeodeztrest--Moscow Geologic and Geodetic Trust

Mosgorgeoltrest--Moscow City Trust of the Geological, Geodetic, and Map Service of the Executive Committee of the Moscow City Soviet of Workers' Deputies

NATI--Automobile and Tractor Scientific-Research Institute

NIGI--Scientific-Research Institute of Hydraulics

Promstroiproekt--see Lenpromstroiproekt

Sibgiprotrans--Siberian State Institute for the Planning of Transportation

Ukrvzryvprom--Ukraine Explosives Industry

VNII--All-Union Scientific-Research Institute

VNIIGS--All-Union Scientific-Research Institute for Hydraulic and Sanitary Engineering

Chapter IV

THE DEGREE OF PRECISION IN GEOLOGICAL EXPLORATION OBTAINED BY VIBRODRILLING

§ 20. EVALUATING THE DEGREE OF PRECISION IN GEOLOGICAL EXPLORATION WHEN DRILLING WITH MANUAL PERCUSSION-ROTARY EQUIPMENT

The principal task in exploratory drilling is to gain a picture of the geologic sections that most precisely reflect the constitution and structure of the soil layers. The problem, therefore, of the precision of the sections obtained by vibrodrilling is most fundamental. However, before we cite data on this matter, it is necessary to examine briefly the outlines of the techniques most frequently employed at the present time in manual percussion-rotary drilling and the precision of the geologic data obtained in this way. This will permit us to compare vibrodrilling with the existing methods of exploration and to draw more objective conclusions.

In engineering-geologic investigations the information on the geologic section should include the following features in the soil sequence:

1) the sequence of layers, their thicknesses, and the location of their contacts;

2) the structural and textural features of the soil (bedding, fracture, type of structures, inclusions, admixtures, segregations, etc.);

3) density and consistency of the soil in its natural state;

4) water content of the layers drilled through.

In addition, the drilling process should be such that it is possible to collect samples (still preserving their natural properties) for use in laboratory experiments.

Let us consider how well these features are represented in manual percussion-rotary drilling.

In this type of drilling the working tip or end may be an auger, a spoon, a sludge barrel, or a chisel.

The auger, or spiral bit, operates on the principle of the corkscrew, being forced into the ground as it is rotated. In this process the soil enters the screw threads of the auger as a coiled ribbon and is extracted with the auger when the instrument is raised. Augers are used in friable, chiefly clayey soils; loose (sandy) soils do not hold together in the threads of the auger, and are drilled by a spoon instead. The spoon is a short barrel with a longitudinal slit and with a cutting edge on the lower part, bent inward. As the end rotates the soil is planed from the bottom in a thin shaving, which fills the hollow part of the spoon. A spoon is also used for cleaning holes.

A sludge barrel consists of a barrel with a valve and is driven into the ground by percussion. During a blow the valve at the bottom opens and the soil enters the barrel. A number of blows more or less fill the barrel, after which the device is removed from the hole and the soil is removed. Sludge barrels are used in saturated sandy soils, in fine-grained gravels, and in muds, i.e., under circumstances in which other bits could not capture and raise the soil.

A chisel is used for breaking up strong rocky layers and boulders; the crushed fragments are extracted from the hole by a spoon or a sludge barrel.

As may be seen from this discussion, the soil that is taken from a hole during manual percussion-rotary drilling and used for lithic descriptions and the preparation of the geologic section is subject to considerable deformation. The least deformation, relatively, occurs during auger drilling in plastic clayey soils. In this type of drilling, when the hole is sunk only to a depth equivalent to the length of the effective part of the bit, the soil is merely

planed off and drawn into a ribbon with no great disturbance to the sequential occurrence of the soil layers. When drilling with a spoon the soil is driven into the barrel in the most unordered form, and particles and aggregates are variously intermixed; consequently the structural and textural features are not well preserved. When a sludge barrel is used for drilling, as is clear from the description of the technique, the soil is thoroughly intermixed; when the soil is extracted from the barrel, it is generally a compacted confused mass of dirt, the natural structures being completely destroyed.

It should be noted, however, that the principal elements of the geologic section—the sequence of layers, the position of contacts, the presence or absence of inclusions, and the general lithic character of the soil—are all fairly reliably determined by manual percussion-rotary drilling. These features may be observed when the drilling is done in a certain way, when a single penetration of the bit does not exceed a depth equal in length to the effective part of the bit (the sampling device), when consideration is given to slumping of the soil during raising of the drill, when casing is sunk and the hole is cleaned out at appropriate times, and so forth. In this process the drilling of short intervals (not exceeding 0.45-0.5 m) excludes any considerable error in determining contacts between individual layers of the soil. Furthermore, the position of a contact may be corrected by the change in muscular effort required in sinking the instrument, by the change in rate of penetration, by the sound produced by the friction of the instrument in the ground, and by similar factors. Periodic cleaning of the hole bottom and sinking of casing avoid mixing of the soil falling from the bit or from the wall of the hole with the soil in the newly drilled interval. All these regulation requirements permit one to place the position of a contact with a precision of 10-15 cm. In regard to details of the geologic structure, very important in geological engineering investigations, drilling by hand, even when all available data are recorded with greatest care, does not preserve these details. For example, banded clays of soft plastic consistency or muds, which may be drilled only with a sludge barrel, completely lose their fine-bedded character in the samples. Since the soil is taken from the hole in a compacted dirty mass, the relationships between particles in the soil are greatly disturbed. Individual thin layers of weak soils occurring among denser layers are recorded as admixtures in the basic mass of soil when a spoon or auger is used; the true structure of the sequence is thus lost to our view. Drilling by augers in clayey soils sometimes leads to the artificial development of slippage planes, and this creates the impression of slumping and mixing of soils, though this may not be actually true. When a sludge barrel is used in saturated sands, soil is drained off from the bottom of the barrel during hoisting of the instrument and the soil left behind is "diluted," as a consequence of which the soil appears to have a low density whereas actually, under natural conditions, the density may be rather high.

It is natural that, during manual percussion-rotary drilling, one will fail to discern such features of the soil as texture (in the sense adopted by soil scientists), fracturing, attitudes, and differential deformation and crumpling produced by any particular process.

There are also several relatively faint relationships that will not be determined; for example, weakly cemented sandstones, when drilled through, will appear as loose sand in the sample. A similar disturbance of texture occurs also in encountering some inclusions, such as cobbles of weak rocks, and one may gain the false impression that sandy nests or lenses are present in the rock. The actual fact in this respect was clearly established during experimental studies by using both vibrodrilling and manual drilling [25].

It is generally impossible to obtain soil samples with undisturbed structures and textures for laboratory tests when using an ordinary bit. With due consideration to this fact, in practice this problem is solved during manual drilling by using a sampler, i.e., a special device permitting samples of soil to be collected with more or less well preserved structures. However, the use of a sampler is limited, since the device requires a special arrangement for driving it into the ground; this arrangement provides for a single penetration into the ground, not in excess of 10-15 cm, after the bottom of the hole has previously been prepared and cleaned of loose material.

Thus, it should not be assumed that the wide use of manual percussion-rotary drilling for engineering geological investigations at the present time leads to high precision of detail in geologic sections, that it permits all the features of the soil to be determined. As may be seen from the discussion, even when all the technical indices are observed, important details of the geologic structure remain unknown, and this is a flaw limiting this type of drilling operation. It is necessary ever to keep this circumstance in mind when evaluating new methods of exploratory work; in particular, vibrodrilling.

§ 21. PROCESSES ORIGINATING IN SOILS DURING VIBRODRILLING AND THEIR EFFECT ON THE PRECISION OF GEOLOGICAL EXPLORATION

The common view is that mutual and unordered movements of particles and aggregates are associated with vibration in the soil, the result of which should be complete destruction of the natural structure of the soil and accompanying compaction or dilation of the mass. This view is based on experiments with vibration during the erection of earthen structures or during the laying of concrete, where the purpose of the vibration is precisely the compaction of the vibrating material, and in soil this process is unavoidably associated with destruction of structure. When vibration is used for sinking a drilling instrument, there must also occur some deformation of the soil if the vibrating process is not regulated in some way. In friable soils, when vibration is prolonged and when the

instrument does not penetrate, it is possible for the soil within the drill barrel to be completely mixed in approximately the same degree as takes place when a sludge barrel is used. However, as experimental work by the authors has shown, if the vibration process is limited by certain conditions, it is possible to preserve the structures and textures of the soil as they exist naturally.

When using vibrators to sink a bit in the form of a barrel with a sharpened edge on the lower end, the vibration of the barrel is transmitted to the surrounding soil. However, as was shown above, the vibration affects a very narrow zone. This statement is based on data from pits dug where holes have been sunk by vibrodrills. The soil in the test area consists of thin beds of fine sand and loam of plastic consistency (alluvial deposits). In digging it was found that the layers were perfectly preserved next to the walls of the holes, although it might be expected that deformation would be noted here. The same degree of preservation of the layers was also observed in the core sample taken from the barrel.

The sequential occurrence of the beds, the thicknesses of the beds, and the positions of the contacts may be dedetermined with greater precision during vibrodrilling than when holes are drilled manually. These elements are determined by direct measurement. Textural and structural features of the soil may also be ascertained very clearly. Bedding, nature of the contacts between layers, distribution of inclusions, and such features may be clearly observed in the slit of the barrel or along the plane of cutting of the extracted soil column (when the barrel is detached), as well as they may be observed in an open mine. Especially detailed descriptions of the soil sequence may be obtained when a sectional barrel is used for drilling, since the column of the soil sample may be examined from all sides (Fig. 42).

Thin soft layers of weak soil (such as peat or mud), which may be wrongly identified as admixtures during manual drilling, are recognized in their true occurrence during vibrodrilling. Cobbles of weak rocks, which are crumbled during manual drilling and are converted to some friable material, are preserved during vibrodrilling, and may be observed in their natural state. If necessary, it is possible to measure the attitudes of the layers directly in the soil sample during preliminary orientation of the drill barrel before lowering it or on extracting it from the hole.

In one region, where the experimental areas are underlain by morainal loams, alluvial deposits, and Upper Devonian variegated clays, sections were compared by data from holes drilled by the Lengiprotrans vibrodrilling rig and by hand, with subsequent verification of the sections in test pits. The holes were spaced 0.4-0.5 m apart; later the pit was dug so that one of its walls passed through the line of centers of the holes (Fig. 43). This procedure permitted one to see directly, in the natural mode of occurrence, all the varieties of soil drilled through and to observe the distinctive features, thus insuring the maximum opportunity for comparing the results. In order to insure objective results, the holes and the pit were studied and described by various investigators.

The investigations have shown that the density and consistency of soil samples taken from barrels used in vibrodrilling agree closely with the natural conditions. This agreement is such that not only does it dispel doubt concerning visual determination of the indicated features, but it gives reason to believe that the samples obtained may be used for laboratory tests.

Thus, when the vibrodrilling process is regulated, the precision of data concerning the geologic section and the details of structure is considerably higher than when holes are drilled by hand. The effectiveness of vibrodrilling, in this regard, approaches exploration of soil by test pits, which are known to be the most accurate for exploration.

Hydrogeologic observations may be made during vibrodrilling with the same degree of accuracy as during manual drilling.

The water table may be determined generally in vibrodrilled holes by means of a gate valve. There is reason to believe that this level may be determined more reliably in soils with poor discharge, since the vibration increases the permeability of the soil. Water bearing horizons, as in hand drilling, are covered by casing, a smaller diameter pipe being used after the horizon has been cut off.

However, it should be noted once again, that the indicated results may be obtained only by observing a definite procedure of vibrodrilling. When it is impossible to observe the proper conditions, the geologic section is noticeably distorted and errors are introduced into the record. It is well known that such erroneous opinions concerning the sequence of soil may also arise during manual percussion-rotary drilling if the drilling procedure has been disturbed.

In this connection, and in order to define the conditions necessary for the drilling procedure, we should examine the deformations arising in soils during unregulated drilling, and we should ascertain the causes of these deformations and the means of eliminating them.

§ 22. POSSIBLE DEFORMATION OF SOILS DURING VIBRODRILLING

Fig. 42. Soil sample from a vibrodrilled hole. The photograph shows that the fine bedding is undisturbed.

Deformation may arise in any of the following ways. During the first penetration of the drill, i.e., in the first interval below the surface, the length of the soil column in the barrel sometimes proves to be less than the length of the interval penetrated. Some of the soil is lost, as it were; i.e., there occurs what is called in core drilling incomplete recovery of the core. On further penetration this phenomenon disappears and the column of soil in the barrel corresponds to the length of the interval passed through. This type of deformation appears most strongly developed when a dense sod cover is present over dry friable soil; it develops in the way indicated below. When the barrel first penetrates the ground, the vibration of the barrel and of the adjoining ground is strongest, since there is no friction between the barrel and the walls of the hole. The dense sod, with its mesh of plant roots, forms a plug on first entering the barrel, and the friable soil below is partly squeezed aside, partly compacted, the consequence of which is an incomplete representation in the core. However, it is sufficient for the drill barrel to penetrate the ground 50-60 cm, where the indicated phenomenon disappears, and then core recovery approaches 100%.

The above-noted incomplete recovery of core was observed by us during the drilling of a dry podsol loamy layer that occurs in the upper part of alluvial and morainal deposits. In most sands, where there is little true soil, this phenomenon has not been observed, and recovery of core, even for the first penetration interval, has been complete.

In order to eliminate this disadvantage, it is possible to decrease the number of rotations of the vibrator during the initial stage of drilling, for the preliminary cut through the dense soil-plant cover; one may also polish the inner surface of the drill barrel, since a polished surface greatly decreases the friction of the soil against the walls of the barrel and thus decreases the deformation of the core.

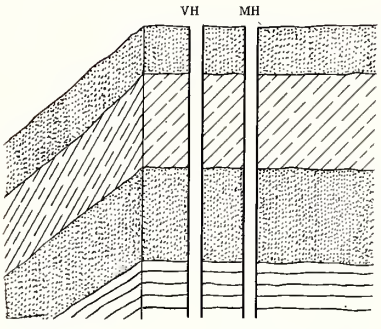


Fig. 43. Disposition of drill holes and test pit for experimental work: VH, vibrodrilled hole; MH, hole drilled by hand.

It should be noted that incomplete recovery of core during the first penetration of the drill, even if the failure cannot be eliminated, has little effect on the accuracy of the geologic section obtained. A complete section in the surface zone may be easily obtained at the hole site by digging a small hole, either before drilling the hole or afterward. Furthermore, the surface zone of the soil, to a depth of one meter, is not generally an object of investigation in geological engineering studies; in this situation the indicated defect has no real significance.

Sometimes one gets the wrong impression and places the contact between two beds at the wrong place (when there is a sharp difference in density between layers of soil drilled through, if the denser soil occurs in the upper part of the section). Examples of this combination are found in dense loams and muds, in dry dense sands, in peat, and in other soils. When such combinations are present, the soil entering the drill barrel forms, as it were, a plug, which is not displaced by the underlying, less dense soil (mud or peat), and the drill barrel penetrates like a pile, forcing the weak soil to the side. When this occurs, the position of the layer of weak soil may be determined after some delay, i.e., after the barrel is raised and cleaned and lowered again for a fresh interval of drilling.

Although such marked changes in density in soils in the indicated sequence are encountered rather rarely, it is always necessary to keep their possible occurrence in mind. The elimination of error in locating contacts in this case may be effected by observing the rate of penetration of the drilling instrument and by measuring the core recovered.

The penetration rate during vibrodrilling in dense and very weak soils (peat, muds) is generally high, but variable. When layers of mud or buried peat are encountered in relatively dense soils, the drill sinks suddenly, as if it had fallen through; this phenomenon permits one to determine the boundary between dense and weak soils. In addition, a corrective check on the position of the contact may be made by measuring the core; this procedure is generally a required part of the logging operation. It is perfectly clear that under such circumstances, i.e., when there occurs a marked change in density of soil, the recovered length of core will be less than the interval passed through by a value equal to the thickness of weak soil that has been pushed aside because of a plug of dense soil in the drill barrel.

Where differences of density are not marked, such confusion in regard to position of contacts does not arise. Lenses and layers of peat in banded clays are recorded in their true position during drilling, although such lenses are observed merely as admixtures during manual drilling (Fig. 44).

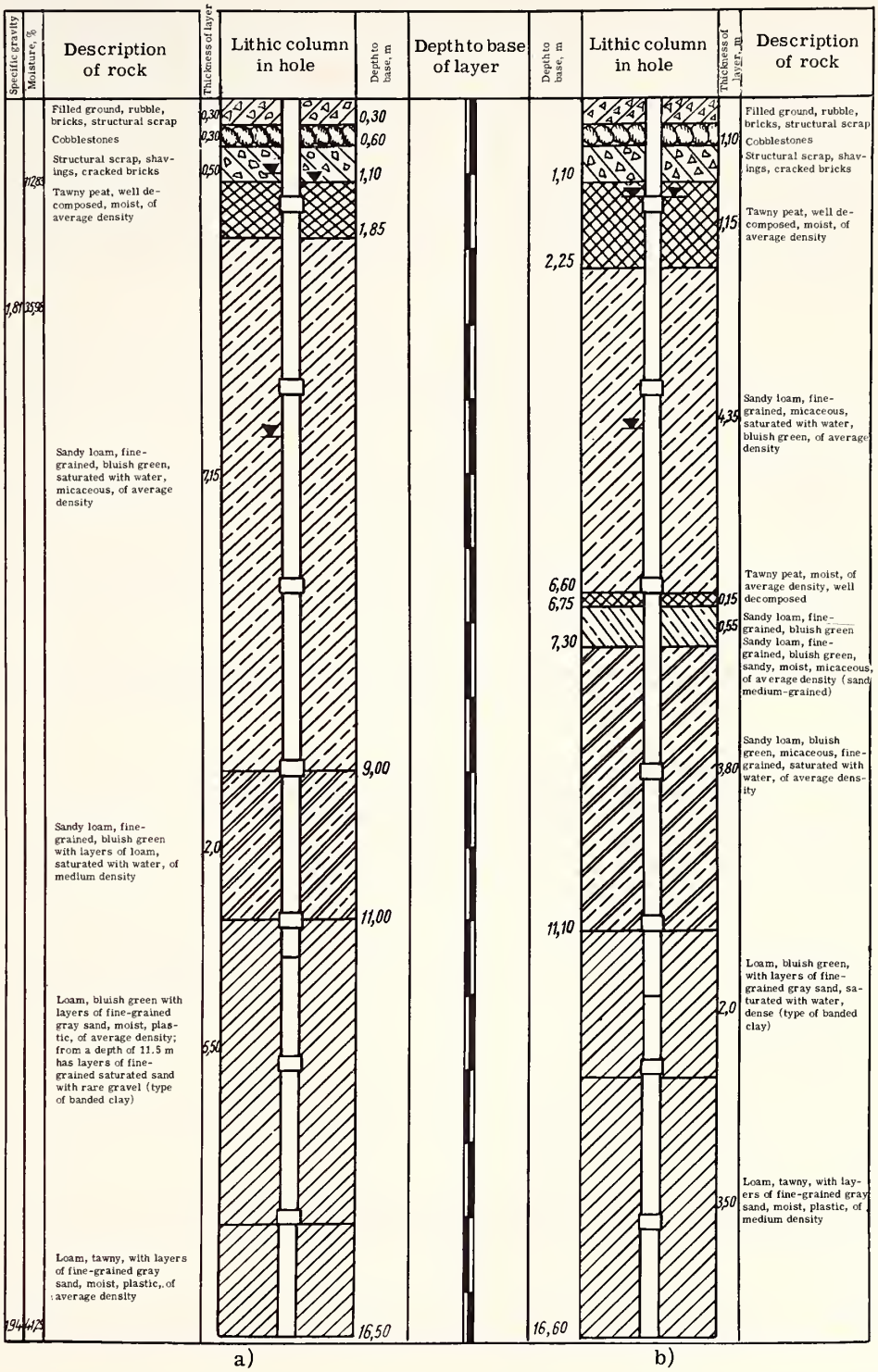

Specific gravity
Moisture, %
Description of rock
Thickness of layer
Lithic column in hole
Depth to base, m
Depth to base of layer
Filled ground, rubble, bricks, structural scrap
Cobblestones
Structural scrap, shavings, cracked bricks
Tawny peat, well decomposed, moist, of average density
Sandy loam, fine-grained, bluish green, saturated with water, micaceous, of average density
Sandy loam, fine-grained, bluish green with layers of loam, saturated with water, of medium density
Loam, bluish green with layers of fine-grained gray sand, moist, plastic, of average density; from a depth of 11.5 m has layers of fine-grained saturated sand with rare gravel (type of banded clay)
Loam, tawny, with layers of fine-grained gray sand, moist, plastic, of average density
0,30
0,60
1,10
1,85
9,00
11,00
16,50
Depth to base, m
Lithic column in hole
Thickness of layer, m
Description of rock
1,10
2,25
6,60
6,75
7,30
11,10
16,60
Filled ground, rubble, bricks, structural scrap
Cobblestones
Structural scrap, shavings, cracked bricks
Tawny peat, well decomposed, moist, of average density
Sandy loam, fine-grained, micaceous, saturated with water, bluish green, of average density
Tawny peat, moist, of average density, well decomposed
Sandy loam, fine-grained, bluish green
Sandy loam, fine-grained, bluish green, sandy, moist, micaceous, of average density (sand medium-grained)
Sandy loam, bluish green, micaceous, fine-grained, saturated with water, of average density
Loam, bluish green, with layers of fine-grained gray sand, saturated with water, dense (type of banded clay)
Loam, tawny, with layers of fine-grained gray sand, moist, plastic, of medium density
a)
b)

Fig. 44. Columns of drill holes: a) drilled by a manual percussion-rotary rig, b) drilled by a vibrodrilling rig.

Thus, errors in determining the position of a contact occur only in rather uncommon circumstances, and these may be allowed for and the position of the contacts corrected.

Soil entering the drill barrel in the form of a column (core) may also undergo marked deformation if the vibration lasts for an extended time. The most widespread type of deformation is a distortion of the contact between two lithically different layers, such as sand and loam. The nature of this deformation is illustrated in Fig. 45. It is obvious that during penetration of the barrel, because of the roughness of the barrel's inner surface, part of the soil of the upper layer occurring next the walls of the barrel is drawn along with the barrel, forcing the underlying soil away from the walls. As a result, a longitudinal section of the core shows a domal-type uplift of the lower layer (Fig. 45a). When the upper layer is drawn along only on one side, a slanted contact is produced (Fig. 45b). As was noted above, this phenomenon occurs when the vibrodrilling procedure is not regulated, and, consequently, these deformations must be considered a consequence of a marked disturbance in the drilling procedure. These observations show that, with a definite (but not too rigid) procedure, these deformation may be kept at a minimum. Under no circumstances should a drill barrel more or less filled with soil be allowed to vibrate in place, i.e., without penetrating deeper. Vibration in place leads to intense stirring of the soil in the barrel, the result of which may be a considerable disturbance to the natural properties. In order to avoid disturbance to the structure of the soil, it is necessary, when penetration slows down or drilling ceases (possibly because the bit encounters denser, hard layers or rock fragments), to raise the drill assembly before normal depth of penetration in order to begin drilling in the dense layer with a clean bit.

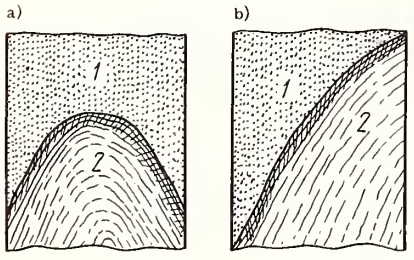


Fig. 45. Deformation of contacts between layers by disturbance of the drilling procedure: a) contact with domal contortion in the lower layer; b) slanted contact--1) sand, 2) clay.

Deformation of the soil during vibrodrilling occurs chiefly in the part of the core adjacent to the walls of the drill barrel. The central part of the core generally remains undeformed. The best results may therefore be obtained by using a drill barrel of large diameter during vibrodrilling (100 mm or greater).

The effect of duration of vibration on disturbance to the natural properties of soil may be seen from Table 20. This table shows the dimensions of the recovered core, i.e., the percentage ratio between length of recovered core and the length of interval drilled through, depending on the time required to sink the barrel (the time during which the ground was subject to vibration).

As seen from Table 20, in all cases when the time of vibration in drilling a single interval up to one meter in length did not exceed 90 sec, the core

Table 20

Effect of Duration of Vibration on Recovery of Core

No. of hole	Drilling interval, m	Length of drilled interval, m	Duration of vibration, sec	Core recovery, %	Remarks
4	1.00-2.00	1.00	90	100	Hole drilled with a sectional barrel
4	2.00-2.45	0.45	20	100	
4	2.45-3.35	0.90	240	88	Ground is alluvial loam, sandy loam, and fine-grained sand
4	3.35-4.35	1.00	15	100	
5	1.00-2.00	1.00	50	100	
5	2.00-3.00	1.00	15	100	
5	3.00-4.00	1.00	15	100	

recovery was 100%. When the time increased to 240 sec, the recovery of core, other conditions being the same, amounted to 88%.

M. G. Efremov [34] has shown that the duration of vibration should not exceed 2 min when drilling in sandy soils and should not exceed 3-4 min in clayey soils. Drilling should cease as soon as the penetration rate decreases to 0.3 m/min.

This same author recommends that the first 2-4 m be drilled in sections no greater than one meter each, regardless of the penetration rate, because of the possible squeezing of the soil in the upper layers.

The natural properties of soils in samples obtained by vibrodrilling are best preserved, furthermore, by proper selection and regulation of the amplitude and frequency of oscillation. It is impossible at the present time to give exhaustive recommendations on this matter in view of the limited experimental data. Preliminary data permit us to state that the best results may be obtained with comparatively small amplitudes. The frequency should be minimal, but sufficient to insure penetration of the drill; this depends on the density of the soil. When the time of

vibration is short (during the penetration of intervals of the order of 0.5 m), the frequency is of no significance.

The preservation of samples also depends on the type of drill bit. In our experiments we used barrels prepared from sludge pumps of standard rigs, 127/115 and 89/78 mm, in which the valves had been removed, the lower edge sharpened, and a longitudinal slit, 50-80 mm wide, made the entire length of the barrel except for 15 cm at the lower end. In addition, a sectional sampler was used (Fig. 17), which was described and appraised above.

There is no doubt that the state of the inner surface of the drill barrel, the sharpness of the cutting edge, and the lubrication of the barrel walls by active substances also affect the degree of preservation of samples.

The greatest disturbance to the natural properties in the soil should be expected when drilling in muds and clayey soils that possess low density and little strength ("frail structure"). As is well known, the recovery of samples with undisturbed structure in such soils, even by means of an ordinary sampler, is not possible, and samples obtained in this way show marked deformation—bent and crumpled layers. When an ordinary bit is used for drilling, such as a sludge barrel, which is scarcely a unique method in this case; the structure of the soil is completely destroyed and the soil is extracted from the hole in a dirty loose mass.

When sinking holes in such soils by means of a vibrator, deformation of the samples also occurs, but if the diameter of the barrel (108 mm) is sufficiently large, the middle part of the sample retains its natural properties and permits us to ascertain the actual character of the soil. Drilling in such soils with "pipe in front," i.e., after first sinking casing pipe and then drilling out the "plug," is not recommended. Experiments have shown that this procedure leads to double deformation of the soil, first from sinking the pipe and again during insertion of the drill assembly in the column of soil within the pipe. Such a technique causes strong crumpling of the layers and the development of microfolds, as were clearly observed by us in drilling holes in banded clays at one of the Leningrad sites.

At the same time it should be noted that drilling in such soils without sinking pipe, even in small intervals, is practically impossible, since the walls of the hole quickly slump. Therefore, when drilling holes in muds and clayey soils of low compaction, as in gravels, it is recommended that casing be driven at the same time the hole is drilled, the bit preceding the foot of the pipe by 0.30-0.40 m. In view of the low density of the soil, the simultaneous driving of casing and sinking of the drill barrel offers no difficulty; it insures the least deformation of the soil samples and does not cause slumping of the walls of the hole.

It is obvious that one cannot also expect to preserve the natural properties of the soil when drilling in friable dry sands of high porosity, where even the slightest vibration disturbs the structural arrangement and produces a denser packing. This phenomenon will appear outwardly as an incomplete recovery of the core, and the error will apparently remain uncorrected; at the same time, the phenomenon may be used to appraise some properties of the ground, since a diminished core recovery in sandy deposits (under normal drilling procedure) will indicate a high porosity in the sands, a capacity for compaction, and, under certain conditions, extensive settling of structures erected upon them.

In compact sands and sands of moderate compaction, there is practically no compaction during vibrodrilling. Parallel determinations of bulk weight of the sands in the samples taken from a vibrodrilled hole and from a test pit dug at the site of the hole are shown in Table 21.

Table 21

Bulk Weight of Fine-Grained Alluvial Sands in Samples from a Vibrodrilled Hole and from a Test Pit

Sample depth, m	Bulk weight, g/cm³ (dry)	
	From the vibrodrilled hole	From the test pit
2.50-2.55	1.55	1.55
3.00-3.05	1.46	1.46
3.80-3.85	1.70	1.69

§ 23. ESTABLISHING THE DEVIATION IN NUMERICAL VALUES OF SOIL CHARACTERISTICS DURING VIBRODRILLING

In order to ascertain the deviation in numerical values of the laboratory characteristics of soils during vibrodrilling, the authors conducted special investigations. For this purpose parallel determinations were made on several indices for samples taken from a vibrodrilled hole and from a test pit at a single site. The hole and the test pit were so placed that one wall of the pit coincided with the axis of the drill hole, cutting the hole on a diameter; this arrangement permitted a comparison of samples taken directly next to each other. As the experiment

showed, when a considerable distance separated the localities from which the samples were taken, even from a single layer, some deviation in the numerical values of the indices of the soil properties was noted, the result of natural inhomogeneity in the sequence.

With due consideration to this, and also to gain completeness and objectivity of the compared results, two samples were taken from the test pit at each depth interval, one to the left, one to the right of the vibrodrilled hole. The distance between points of sampling did not exceed 0.50 m, and the distance between corresponding points in the test pit and in the vibrodrilled hole was 0.20-0.30 m.

The principal laboratory characteristics of soils for comparing samples from the test pits and the vibrodrilled holes were taken to be natural moisture and bulk weight under conditions of natural moisture. From these data, determined directly in the field, the dry bulk weight, porosity, and moisture content were computed. Some samples were used for penetration tests with a cone.

The vibrodrilled holes and the test pits were made in alluvial deposits consisting of sandy loams, loams, and fine-grained sands. The sands were dry and slightly moist; the loams became plastic only with difficulty and had a semisolid consistency. There were no water-bearing horizons in the sequence drilled or cut by the test pits. The grain-size distribution in the alluvial soils is shown in Table 22.

Table 22

Grain-Size Distribution in Soils of the Alluvial Sequence

Depth, m	Content (in %) of particles (dimensions in mm)								Type of soil
	1-0.5	0.5-0.25	0.25-0.10	0.10-0.05	0.05-0.01	0.01-0.002	0.002-0.001	0.001	
0.90-0.95	0.2	3.5	32.5	16.4	14.8	12.1	3.3	17.2	Heavy loam
1.35-1.40	0.1	2.2	40.2	18.1	11.6	10.7	3.2	13.9	Medium loam
1.70-1.75	0.1	3.7	50.0	28.3	10.6	3.8	0.3	3.2	Light sandy loam
2.00-2.05	0.5	20.4	49.5	13.1	10.1	3.4	0.5	2.5	Fine sand
2.20-2.25	1.1	15.9	37.7	21.2	12.0	5.7	0.9	5.5	Heavy sandy loam
2.50-2.55	1.8	15.0	50.0	23.1	5.9	1.7	0.7	1.8	Fine sand
3.00-3.05	0.1	3.2	57.2	31.4	6.7	0.7	0.7	—	The same
3.80-3.85	1.3	15.0	42.7	15.8	21.7	2.4	0.2	0.9	" "
4.00-4.05	0.1	5.0	55.2	24.0	11.1	2.1	2.5	—	" "

It should be noted that the alluvial sequence in which the comparative studies were made is of rather spotty composition. The upper part of the section, to a depth of 1.7-2 m, consists of an alternation of thin lenticular layers of sandy loam and loam. Below this, fine-grained sand is dominant, but here also are found thin layers of loam and humic seams (of buried organic material, apparently having been introduced by some past stream and having been subjected to decomposition since that time). The indicated spottiness may naturally be reflected in the comparative indices.

The results of comparison of the above-mentioned laboratory characteristics of soil from the vibrodrilled holes and from the test pits may be seen in the graphs of Fig. 46. The numerical values of the indices and the differences in values for test pit and vibrodrilled hole are shown in Table 23.

One could not generally expect complete coincidence of the laboratory characteristics for the vibrodrilled holes and the test pits. Even though the vibrodrilled holes are situated in the plane of a wall of a test pit, the absolute values of the laboratory characteristics may differ because of inhomogeneities of the soil. This fact is confirmed by comparing the characteristics of samples taken from different places on the same wall of a test pit. It is in this way that we may explain the more or less impressive variations in the upper part of the section, where the composition is spotty (alluvial loams interbedded with sandy loams). *Within a homogeneous sequence* (from 2.5 to 3.85 m), composed of fine-grained sands, *almost perfect agreement was observed in the comparative values of natural moisture content and other soil characteristics.*

In examining the graphs (see Fig. 46) that show the comparative data for samples from vibrodrilled holes and a test pit (two values are taken for the pit, one from the left and one from the right of the vibrodrilled hole), in keeping with the method of investigation adopted, the following data come to one's attention.

The indices characterizing the properties of the soil samples taken from the pit, from a single layer at the same depth and from the same wall of the pit (to the right and the left of the vibrodrilled hole), are close to each other, but they are not absolutely identical. Variations in the value of natural moisture content are generally

Table 23

Soil Characteristics of Samples from a Vibrodrilled Hole and from a Test Pit

Sample depth	Natural moisture content, %		Bulk weight with natural moisture, g/cm³		Bulk weight dry, g/cm³		Porosity, %	
	Vibro-drilled hole	Test pit	Vibro-drilled hole	Test pit	Vibro-drilled hole	Test pit	Vibro-drilled hole	Test pit
0.90-0.95	13.95	18.49	1.87	2.05	1.63	1.73	37.69	36.20
1.35-1.40	21.61	19.98	2.07	2.03	1.70	1.69	37.27	36.30
1.70-1.75	21.15	22.78	1.99	1.96	1.64	1.73	39.26	35.20
2.20-2.25	13.26	12.15	2.07	1.84	1.78	1.64	34.32	38.60
2.50-2.55	6.32	6.46	1.66	1.66	1.55	1.55	41.73	41.80
3.00-3.05	12.25	8.57	1.66	1.61	1.46	1.46	40.93	44.90
3.80-3.85	8.78	8.04	1.85	1.81	1.78	1.69	36.52	37.18
4.05-4.10	14.95	21.40	2.00	1.88	1.70	1.54	37.27	42.60

1-2%, reaching 6% in individual cases (in the depth interval 0.90-0.95 m). Differences in bulk weight with natural moisture content are 0.05-0.10 g/cm³, reaching 0.14-0.17 g/cm³ in individual cases. The dry bulk weight also varies within the limits of 0.05 to 0.15 g/cm³, and the porosity ranges from 2 to 3%; the water saturation is 0.10-0.15. Although these differences are small, they definitely indicate that the natural properties of the soil fluctuate within a single layer. This circumstance is due to the nature of the investigated sequence, the composition of which is not ideally homogeneous.

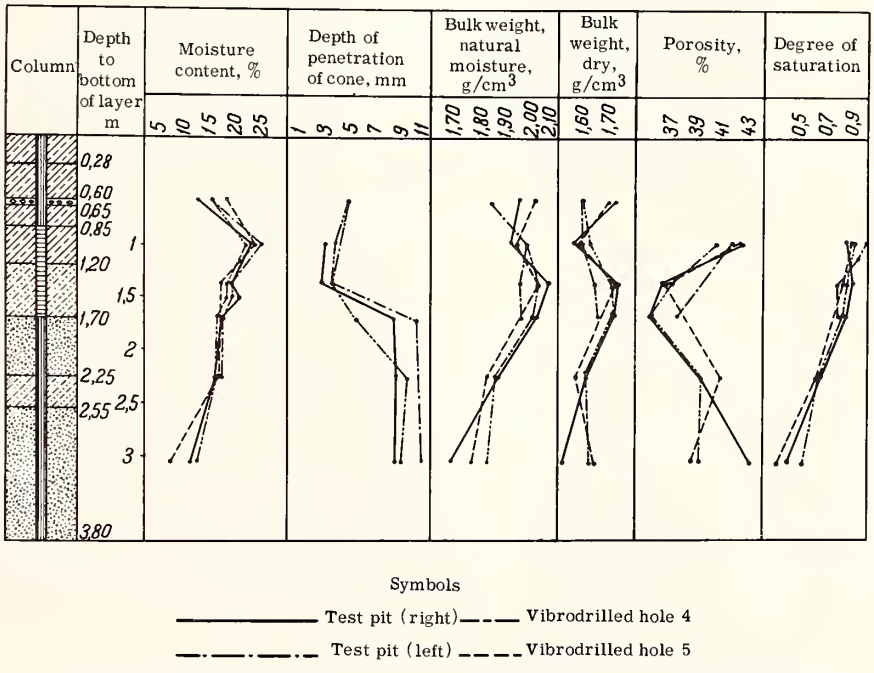


Fig. 46. Comparative graphs of laboratory characteristics of soils from samples taken from a pit and from vibrodrilled holes (the horizontal lines in the column indicate dry soil, the vertical line moist soil).

It is natural that the same characteristics of the soil in samples obtained by vibrodrilling *have no perfect coincidence with the characteristics obtained for samples from the test pit.* The numerical values of these discrepancies for dry bulk weight are shown in Table 24.

Table 24 clearly shows that the differences in values of dry bulk weight for samples taken from the pit and from the vibrodrilled hole do not exceed the differences in these values for samples taken from different sites in the pit

Table 24

Values for Dry Bulk Weight for Samples Taken from a Pit (from Two Sites 0.5 m Apart at the Same Depth) and from a Vibrodrilled Hole

Depth	Test Pit		Vibro-drilled hole	Difference in values between the two sites in the pit	Difference in values between the pit (1st site) and the vibrodrilled hole	Difference in values between the pit (2nd site) and the vibrodrilled hole
	1st site (right)	2nd site (left)				
0.60	1.75	1.60	1.72	0.15	+0.03	-0.12
0.85	1.56	1.61	1.63	0.06	-0.08	-0.02
1.40	1.74	1.65	1.72	0.09	+0.02	-0.07
1.70	1.73	1.68	1.73	0.05	0.00	-0.05
2.40	1.64	—	1.64	—	0.00	—
3.00	1.55	—	1.60	—	+0.05	—

(from a single depth 0.5 m apart). There are no grounds for explaining these differences in measured values by differences in technique of doing the work, i.e., by vibrodrilling, since, if this were true, the variations between values obtained for samples from the vibrodrilled hole and those obtained for samples from the pit should show some systematic pattern, pointing either to compaction or to dilatancy of the soil during vibration. When we refer to the graphs (Fig. 46), it is seen that the curves showing the values of bulk weight and the other physical characteristics of the soil obtained from samples collected in the vibrodrilled holes are, as a rule, near the corresponding curves, or between the curves, for samples taken from the pit.

The similarity of the laboratory characteristics for samples from vibrodrilled holes and from test pits was noted by the authors as early as 1953 [25]. Repeated investigations after this completely supported the first results. This same position has also been confirmed by the data of M. G. Efremov (Fig. 47). Therefore, for the laboratory determination of such characteristics as natural moisture content and bulk weight, and for the porosity and degree of saturation (computed from these values), it is completely satisfactory to use samples taken directly from a soil column (core) obtained during vibrodrilling. However, this does not exclude the use of a sampler, when conditions require it, for controlled determinations during geological engineering studies under vital structures.

§ 24. BRIEF INSTRUCTIONS ON VIBRODRILLING OPERATIONS AND THE BASIC CONDITIONS REQUIRED FOR OBTAINING DATA FROM THESE OPERATIONS

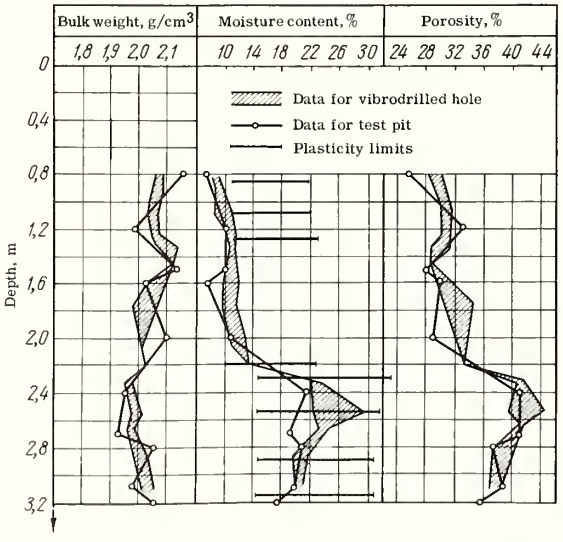


Fig. 47. Comparative graphs of laboratory characteristics for soils taken from a test pit and from a vibrodrilled hole (after M. G. Efremov).

To describe the geologic section with great precision from data obtained by vibrodrilling, as with any other type of geological exploration, it is necessary to observe certain conditions.

Preparation of the Drill Assembly for Beginning Operations and for Penetration. The drill bit should be carefully cleaned of soil, outside and inside, before lowering and beginning to drill. When necessary the barrel should be washed with water in order to remove completely adhering patches of soil, which increase the roughness of the inner surface of the barrel. The threaded couplings should also be cleaned of soil, rust, and lubricating oil. When any crumpling of the cutting edge of the drill bit (or of the shoe) occurs, it is necessary to remedy the fault. The edge of the barrel should be evenly sharpened.

The drill assembly should be carefully measured so its length will be precisely known. It is also necessary to make chalk marks on the instrument at 0.5-m intervals, in order to observe the penetration rate. At the first penetration these marks are placed on the bit proper; in subsequent penetrations they are placed on the rods or the pipes that extend above the ground surface as the drill is lowered to the bottom.

Centering and Insuring a Vertical Axis for the Hole. The location of the hole should agree precisely with the arrangement of the hoisting apparatus, being determined by a plumb line to coincide with the direction of the cable through the hoist block. When operating with a vibrator situated above the column of rock, it is necessary to keep in mind that the drill assembly suspended on the cable, with the attached vibrator, does not mark the exact position of the hole, since the center of gravity of the vibrator may not lie on the plumb line passing through the point of suspension. Therefore, the center of the hole must be determined by a special plumb line, not by the drill assembly suspended from the cable. One should also keep in mind that the drilling derrick, if it is used for raising and lowering, may change its initial position under the load of the drill string because of sinking of the legs into the ground. Therefore, the center of the hole may be marked only after the derrick has assumed its final position, considering the load of the vibrator and the drill assembly.

Proper centering is very important, since it insures that the hole will be vertical.

Beginning Operation and Sinking the Drill Assembly, and Observations Made at This Time. During the first penetration, beginning at the ground surface, the vibrator is attached directly to the drill bit. The bit is placed at the marked center of the hole in a strictly vertical position, and the vibrator is then turned on. To maintain the vertical position of the drill during the first penetration, if there is no special attachment (a directional brace), this segment is drilled by hand. The depth of this first interval should not be greater than 1.0-1.2 m.

Insuring a vertical direction in drilling the hole is the fundamental condition for effective operation of the vibrodrilling rig. Inclination and bending of the hole not only make it difficult to extricate and raise the drill, but cause more intense vibration of the soil in the barrel, and this leads to greater disturbance to the natural properties. Therefore, if for any reason the hole becomes bent during the first penetration, it is advisable to begin a new hole, knowing that the loss of time so incurred will be negligible.

In drilling it is necessary to determine the penetration rate and also to note changes in the rate within each interval of penetration. The purpose of this is to improve accuracy in locating contacts between weak and hard layers and, chiefly, to gain data for evaluating the density of the soil in regard to suitability as a base for buildings. In addition, observations on penetration rate are made in order to avoid vibration of the instrument when penetration slows down or stops. When penetration does slow down or stop it is necessary to shut off the vibrator and to raise the drill assembly. Prolonged vibration when the instrument is not penetrating leads to disturbance of the natural properties of the soil.

The depth of drilling for a single penetration depends on a number of conditions, but chiefly on the properties of the soil and the penetrating ability of the rig (which determines the penetration rate). The greater the penetration rate the greater the interval of a single penetration may be without disturbing the structure of the soil. When the penetration rate is high (1 m/min or greater) a single penetration the entire length of the drill barrel may be permitted, i.e., practically 2-2.5 m. If the penetration rate is only 0.2-0.3 m/min, single penetrations greater than one meter are not recommended. Short penetrations should also be made in especially friable (sandy) soils, where more or less prolonged vibration leads to marked deformation. Quick soils should be drilled with a valve in the drill barrel (vibratory sludge barrel).

When an interval has been drilled, the remainder of the drill column is measured to determine the depth to bottom and to determine the length of the penetrated interval. The instrument is then raised. When it is difficult to loosen the bit from the bottom, it is permissible to run the vibrator a short time with tension on the cable, but great care must be exercised because there is danger of the soil in the barrel being thrown out.

Descriptive Records and the Collection of Samples. The raised drill barrel is unscrewed from the rest of the drill string and is placed on a board. If the drilling has been made with a slitted barrel, the slit must be cleaned in order to expose the integral soil column within the barrel. When a sectional barrel is used (a sampler), the barrel must be taken apart in order that the entire soil column may be observed. When this is done note is taken of whether soil has been thrown out of the lower part of the barrel, and a "foreign layer" in the upper part of the barrel is distinguished when such loss has taken place. When soil has been lost, the bottom depth is corrected; i.e., the drilled interval is diminished by the amount of material lost, and this correction is recorded.

A necessary part of the record is the determination of core recovery (in percent), as is done in core drilling. To do this the length of the column of extracted soil is measured (without computing the foreign layer), and this value is divided by the length of the drilled interval. One hundred percent recovery should be striven for. A recovery of less than 80% should be considered a flaw in the operation.

The position of the contacts, when the recovery of core is one hundred percent, is determined by direct measurement from either end. When recovery is incomplete the measurement should be made from the lower end, since this end is the more precisely located (by the position of the drill) and, in addition, because the lower part of the core is generally less disturbed, having been subjected to vibration for a shorter time.

To gain the most precise picture of the geologic structure of the section drilled through, the record should contain a graphic section showing the position and nature of the contacts, the distribution of inclusions, interbedding in the soils, transitions from one soil type to another, and similar features. Breaks due to incomplete recovery of core are not filled in. When the final section is compared with others, the breaks are eliminated by interpolation from examinations of the records as a whole and from proper consideration of the observations made during drilling.

The extracted soil sample is described in a normal order: the soil type is named, and then are recorded the color, the moisture content, the consistency, inclusions, textural and structural features, and other properties. One should keep in view at this time that the outer zone of the core may show displacements on the order of 1-1.5 cm; therefore, all observations and descriptions should be based on the central part of the soil column.

Samples for laboratory investigations are collected by separation with a cutting ring in the central part of the soil column. For control it might be recommended that samples be taken with an ordinary sampler after first cleaning the hole bottom by hand with a drilling spoon.

Hydrogeologic Observations. The appearance of water in a hole during vibrodrilling is determined in the same way as during manual drilling, by moistening of the drill bit and by splashing heard when the drill is lowered to the bottom. The depth to the water is ascertained by appropriate measurements on the length of the drill string. Having established a water level in the hole, the position may be determined with an ordinary gate valve.

It should be kept in mind that, during vibrodrilling, physically bound water may be liberated because of the vibration. Because of this, one sometimes gets a wrong impression of the water-bearing properties of the sequence drilled through, i.e., concerning the presence of free water in the ground. However, if the soil actually contains no free water, the above-indicated factor will not lead one astray, since the reverse transformation of water occurs almost instantaneously, and no accumulation of water will be observed on the bottom.

At the same time, where water-bearing soils with low permeability are present, where the presence of water can be observed in manually drilled holes only after waiting a day, vibration fosters more rapid discharge of water from such soils and permits the timely identification of water-bearing layers.

Reinforcing Holes with Casing. Where walls in the hole are unstable, and also where water-bearing horizons are to be sealed off, the holes are reinforced with casing pipe. The casing is emplaced with the aid of a vibrator connected through an adapter to the pipe. As the casing is driven into the hole, more pipe is added. It is advisable, after sinking the casing, to clean the hole and to remove the plug by manual operation, with a spoon on a percussion-rotary rig. When sealing off a water-bearing layer for further drilling, a bit of smaller diameter is used.

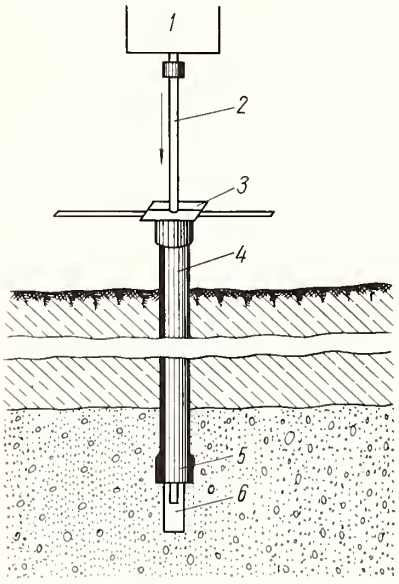


Fig. 48. Drilling a hole with a vibrodrilling rig with simultaneous sinking of casing: 1) vibrator, 2) drilling rod, 3) swivel collar, 4) casing pipe, 5) shoe of casing, 6) bit (sonde).

In unstable soils that do not permit holes to be sunk below the shoe of the casing, the casing is driven at the same time the drilling is effected. To accomplish this, a swivel collar is attached to the rods and the drill assembly is let down inside the column of pipe; the drill bit precedes the shoe of the casing by 0.20-0.25 m (Fig. 48). During operation the vibrator simultaneously activates the drill bit and sinks the casing. In this way muds, medium and fine gravels, and saturated sands (including quicksands) may be drilled.

Dismantling of Holes. The casing pipe is also extracted from the holes by means of a vibrator attached through an adapter to the column of pipe. With operation of the vibrator a winch or hoist simultaneously raises the column. Because of the vibration, the friction between the pipe and the soil is sharply decreased, and it is not difficult to raise the casing.

§ 25. SUMMARY

At present we may consider the following statements to be rather reliably substantiated:

1) the precision of a geologic section constructed from data obtained by vibrodrilling, including details concerning the geologic structure, is higher than when manual percussion-rotary methods are used, and, in no case, is it lower;

2) the preservation of samples obtained by vibrodrilling depends to a considerable extent on the vibrodrilling procedure and the type of bit employed;

3) when a definite procedure is followed during vibrodrilling, it is possible

to obtain samples in a very good state of preservation and, in many cases, to use these samples directly in laboratory tests;

4) in keeping with what has been said above, vibrodrilling operations must be conducted in conformity with definite technological rules, as is true with other types of geological exploration.

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